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GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

1954

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San Francisco
Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

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LETTER OF TRANSMITTAL

The Honorable Goodwin J. Knight
Governor of the State of California

DEAR SIR: I have the honor to transmit herewith Bulletin 170, *Geology of Southern California,* prepared under the direction of Olaf P. Jenkins, Chief, Division of Mines, Department of Natural Resources. This report consists of ten chapters, five geologic road guides, and thirty-four separate geologic maps upon which are printed brief texts. Bulletin 170 has been prepared in cooperation with an organizing committee of the Geological Society of America. The principal editor is Dr. Richard H. Jahns, professor of geology at the California Institute of Technology. Four other members of the committee consist of Dr. A. O. Woodford, professor of geology, Pomona College; Dr. John C. Crowell, professor of geology, University of California at Los Angeles; and two members of the Division of Mines, L. A. Norman, Jr., and Lauren A. Wright. This committee was assisted by 103 contributing authors, representing many different agencies.

As a result of the enterprise, a comprehensive treatise has thus been prepared on every principal phase of the geology and mineral resources of southern California and is issued as one of the series of the Division of Mines' informative and technical publications. It should provide basic information of great value and broad scope in the general understanding and scientific study of all natural resources in California, in engineering problems, as a background for the development of mining, oil and gas, and various other industries wherever minerals are utilized. The volume should serve as a guide and aid to the interested traveler who seeks to know the why and the wherefore of the rocks and landscape he views.

Respectfully submitted,

DEWITT NELSON, Director
Department of Natural Resources

September 23, 1954

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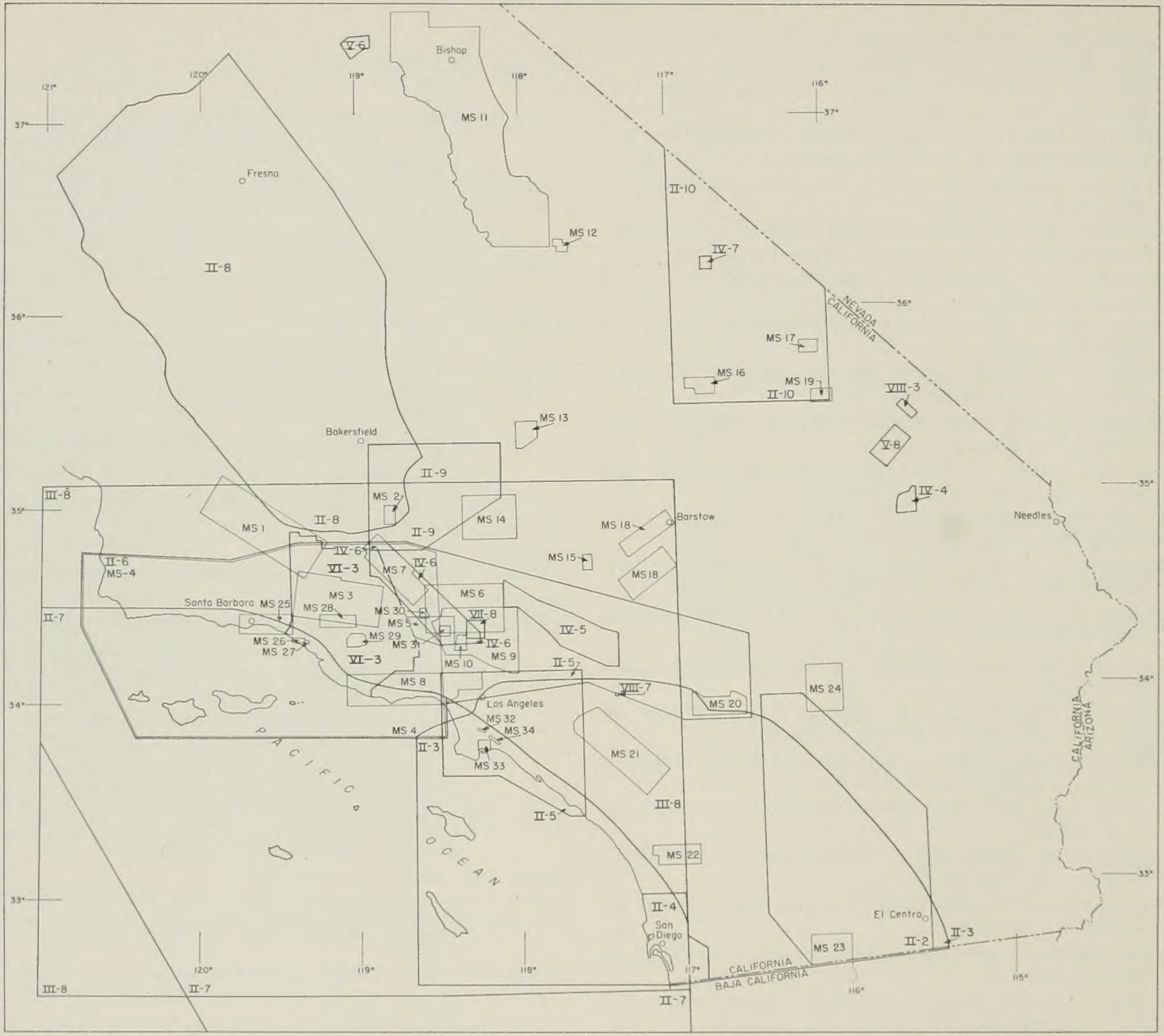

Index map of southern California, showing areas covered by geologic maps in this volume. Map Sheets are designated by the prefix MS. Each of the other maps is identified by means of a Roman and an Arabic numeral, which designate the chapter and individual contribution, respectively, in which the map appears.

PREFACE

During recent years many persons have felt a growing need for an up-to-date summary of southern California geology, and for discussion and interpretation of major problems that have been recognized. Little more than two decades has elapsed since the U. S. Geological Survey published the southern California guidebook for the Sixteenth International Geological Congress, but an enormous amount of new information has become available during this period of time. Further, emphasis in this earlier volume was placed mainly upon the geology of the younger rocks in the coastal parts of the region, and a similar emphasis has characterized Ralph Reed's *Geology of California* and other important summaries that have appeared in later years. A balanced treatment for the entire region has not been attempted heretofore, in large part because of marked differences in the knowledge of different areas.

The present volume was conceived by a small group of geologists who were responsible for organization of field trips in connection with the 1954 Annual Meeting of The Geological Society of America in Los Angeles, and in a sense its preparation was an immediate outgrowth of the need for field-trip descriptions. Fundamentally, however, it was intended to fill a much broader and more continuing need. A work of this scope could not have been the product of any one man's efforts, because of the overwhelming mass of information that had to be assembled, collated, understood, and interpreted—and perhaps in part because the profession lacks a present-day Ralph Reed. Thus the simplicity of arrangement and continuity of thought that distinguish the classic *Geology of California* are largely absent from this more comprehensive treatment.

Organization of this book was the work of a five-man committee of The Geological Society of America, comprising John C. Crowell of the University of California at Los Angeles, Richard H. Jahns of the California Institute of Technology, L. A. Norman, Jr., and Lauren A. Wright of the State Division of Mines, and A. O. Woodford of Pomona College. The work of these men was facilitated by advice and suggestions from numerous representatives of industry, State and Federal Surveys, and academic institutions. The volume is intended to provide a broad sampling of geological features and thought, as they relate to the southern California region, and its contents reflect an approach that is partly geographic and partly topical. Emphasis has been placed on a wide variety of contributions by investigators qualified to make authoritative presentations and interpretations of data. Of the 103 contributors, 41 represent universities, colleges, and museums, 20 represent oil companies, 16 are on the staffs of the Division of Mines and other State agencies, 16 are members of the U. S. Geological Survey, 4 represent mining companies and industrial organizations, and 6 are independent geologists.

The 10 chapters of the book comprise 62 papers that deal with physical geography, general geology of the natural provinces, historical geology and stratigraphy, geologic structure, geomorphology, mineralogy and petrology, hydrology, oil and gas, mineral deposits, and engineering geology. Some of the individual contributions are general in scope, others deal with specific areas or problems, and most contain information hitherto unpublished. Supplementing the main part of the book is a group of 34 map sheets of selected areas; each sheet includes a geologic map, which in general is accompanied by other illustrative material and a brief text. Five detailed geologic guides are intended for use by persons who may be interested in field excursions through typical parts of the coastal and interior regions. The Organizing Committee and the Editor have been as objective as possible in developing a framework for this volume consistent with the space and time available for publication, and they assume full responsibility for not including, through wholly practical considerations, a number of additional contributions that were suggested and that might well have improved the final product.

For the present purposes, southern California has been regarded as the region occupied by Imperial, Inyo, Kern, Los Angeles, Orange, Riverside, San Bernardino, San Diego, Santa Barbara, and Ventura Counties, although a few of the contributions deal with parts of adjacent counties. Standardized geographic and geologic terminologies have been followed wherever possible, but the preferences of individual authors also have been respected. Thus the reader will note minor inconsistencies in the use of terms such as thrust fault and reverse fault, formation and group, and area and region. This may disturb some purists, even though few real ambiguities appear to be present. Some features are discussed under different proper names by different authors, but the alternative names are indicated in these instances. Finally, not all geologists interpret certain features in the same way, particularly in regard to age assignments, and such differences of view cannot be edited out merely in the interests of consistency. In general, however, the contributors have been careful to indicate those matters on which serious disagreement exists.

This book could not have been completed without the assistance of many persons whose names do not appear as formal contributors. Among the most helpful of these were Berniece Tomczak and Florence Wiltse of the California Institute of Technology and Geraldine M. Fazzari and Beatrice Reynolds of the State Division of Mines, who typed many hundreds of pages of manuscript; Charlotte Bjornsson of the California Institute of Technology, Richard A. Crippen, Jr., Audrey Jennings, Carl J. Sharits, and Elsa B. Woodward of the State Division of Mines, and Esther T. McDermott of the U. S. Geological Survey, who drafted many of the maps, sections, and diagrams; and Elisabeth L. Egenhoff and Mary R. Hill of the State Division of Mines, whose editorial work on the final manuscripts eliminated numerous errors, inconsistencies, and infelicities of expression, including those derived from previous editing. Charles J. Kundert checked most of the maps and sections, many of which were considerably improved through his careful attention.

Many of the contributions were obtained through the active cooperation of oil and mining companies, the U. S. Geological Survey, the State Division of Mines, the State Division of Water Resources, and a number of colleges and universities. These and other organizations also supplied an abundance of additional data that have been used in this volume. Numerous special photographs were obtained through the courtesy of Herbert E. Haymaker of Fairchild Aerial Surveys, Inc., Charles Jackline and Donald Lewis of Pacific Air Industries, and William C. Miller of the Mt. Wilson and Palomar Observatories.

Those to whom this volume may become useful are indebted fundamentally to Olaf P. Jenkins, Chief of the State Division of Mines, who not only arranged for its publication, but maintained an active interest in the project and made it possible for many members of his staff to assist in bringing it to successful completion. Without his cooperation, this book could have been little more than a collection of annotated road logs.

The Editor wishes to express his personal thanks to all of the authors, most of whom completed their contributions in good form, in good time, and in the face of other and more pressing duties. Also much appreciated were the efforts of Florence Wiltse, and of Thomas E. Gay, Jr., L. A. Norman, Jr., Berdine H. Rogers, Richard M. Stewart, Bennie W. Troxel, and Lauren A. Wright of the State Division of Mines, who willingly contributed numerous special services in final preparation of the book. To Edgar H. Bailey and Henry G. Ferguson of the U. S. Geological Survey go particular thanks for their parts in the completion of several manuscripts.

Richard H. Jahns
Pasadena, California
July 30, 1954

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BULLETIN 170

CHAPTER I
GENERAL FEATURES

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San Francisco
Bulletin 170
December 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER I

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Editorial Note:

CHAPTER ONE is a brief summary of the geography and geology of southern California, a region that includes a remarkable variety of topographic forms and is characterized by numerous climatic contrasts. In large part these features are related to a complex geologic pattern in which a varied assemblage of rock types and structural elements is present. This pattern not only has been of great interest to geologists and other investigators, but it has had a profound influence on human occupation of the region from earliest times.

The three papers in this chapter deal with general relations and problems of geologic application, and a sampling of geologic features is provided by twenty-four individual map sheets that appear in a separate pocket. These sheets include geologic maps, sections, and brief descriptive texts.

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1. INVESTIGATIONS AND PROBLEMS OF SOUTHERN CALIFORNIA GEOLOGY *

BY RICHARD H. JAHNS †

HISTORICAL SKETCH

Period of Early Settlement. Recognition of geologic features and processes by the peoples of southern California dates back at least several thousand years, when Indian tribes lived in some of the coastal areas and on the shores of now-extinct lakes farther inland. These early inhabitants were well aware of earthquakes, floods, landslides, and other natural phenomena, as well as unusual elements of the terrain, and they attempted to explain these things by means of various myths, many of which appear to have been founded upon more careful observations than do some of the scientific explanations of much more recent times!

Later tribes became increasingly aware of rock and mineral materials, and showed considerable skill in correlating their physical properties with specific uses. Thus granite and steatite were converted into utensils, slate and schist into quarrying tools, and obsidian and silica minerals into weapons. Clay was used for making ceramic ware, and asphaltum from numerous seeps was used for waterproofing and as an adhesive. Natural pigments, salt, and gem materials also were in demand. The techniques of search for better materials, and of mining and preparing these materials, were gradually improved, and ultimately at least 131 mine or quarry localities were known to the California Indians (Heizer and Treganza, 1944, pp. 298, 303-340).

Spanish settlement of the region began with the Portolá expedition in 1769, long after the explorations of coastal areas by Cabrillo (1542), Viscaíno (1602), and others. From this time until shortly after the end of Spanish rule in 1847, southern California was a slowly developing agricultural province characterized by large ranchos. The newcomers commonly followed the example of the Indians in selecting areas for settlement, and they used much the same sources of water, bathed in the same hot springs, and worked some of the same mineral deposits that had been known to the Indians. A few of them also indulged in a little mining for placer gold in Imperial County as early as 1775, and later on some mining was done in Recent stream gravels north of Los Angeles and in conglomerates of early Tertiary age in San Diego County.

Period of Geologic Exploration and Early Description. The discovery of gold in the Sierra Nevada in 1848 initiated a period of profound changes in southern California life. The Americans who had come to the coastal areas during earlier years were joined by thousands upon thousands of others, Los Angeles and other towns became important trading centers, and new settlements were founded as most of the large ranchos were divided into numerous smaller holdings. Prospecting and mining flourished in many parts of the region, and new mining camps appeared in the country east and southeast of the Sierra Nevada, as well as in the Coast Ranges to the west. Metal mining was dominant, but important discoveries of petroleum, salines, and other nonmetallic substances also were made.

The earliest systematic work on southern California geology was done in connection with several surveys of mineralized areas and routes of transportation. The expeditions in 1853 and 1854 for railroad routes to the Pacific Ocean yielded descriptions of rocks, fossils, and mineral deposits, and marked the real beginning of integrated observations on the geologic history of the region. From these surveys also came the first reasonably accurate geologic maps of southern California areas (Blake, 1856; Antisell, 1857), and it is interesting to compare them with the much more detailed map data presented years later by Darton (1916, 1933) for the country along some of the same routes. Additional systematic investigations were made in the fifties by the first State Geological Survey, under the direction of J. B. Trask, and in the sixties by State Geologist J. D. Whitney and his staff.

Southern California was linked by rail to San Francisco in 1876 and directly to the east in 1881, and soon afterward tremendous increases in population stimulated geological investigations on many fronts. The U. S. Geological Survey, which had been organized in 1879, sent numerous workers into the region, and by the turn of the century important contributions had been made by Waldemar Lindgren and H. W. Turner in the Sierra Nevada and areas to the east and southeast, G. F. Becker in the Sierra Nevada and the Coast Ranges, and G. K. Gilbert and I. C. Russell in parts of the Basin-Range country. Paleontologic studies had been made by T. A. Conrad, C. D. Walcott, C. A. White, W. H. Dall, T. W. Stanton, and others.

The State Mining Bureau, organized in 1880, was responsible for widespread investigations by H. W. Fairbanks, W. A. Goodyear,

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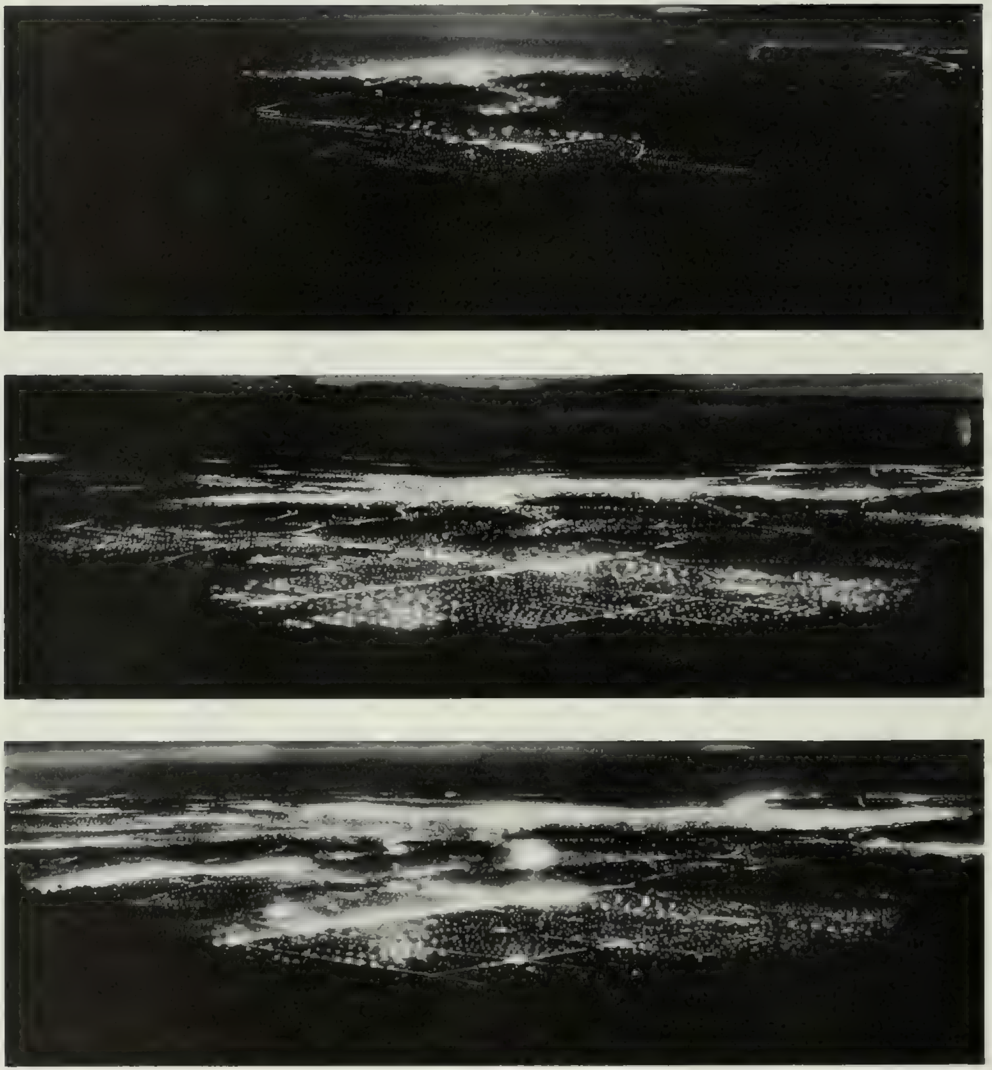

FIGURE 1. The growth of Los Angeles and neighboring cities during a 20-year period, as revealed by nighttime views southwestward from Mt. Wilson, in the San Gabriel Mountains. Top, 1906; middle, 1918; bottom, 1925. Pasadena is in foreground, Los Angeles in middle distance, San Pedro at far left, and Venice and Santa Monica are at far right. *Photos courtesy of Mt. Wilson and Palomar Observatories.*

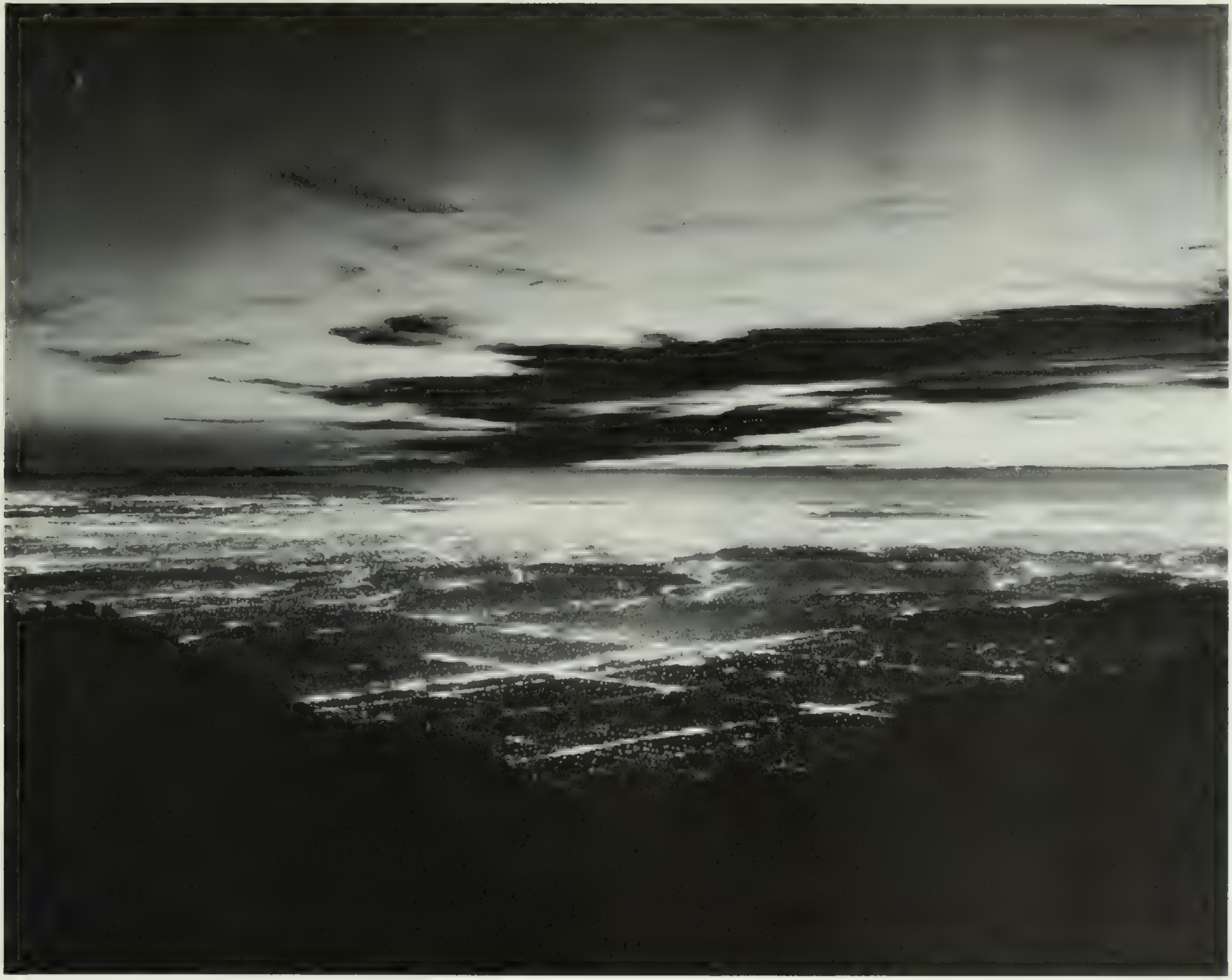

FIGURE 2. Nighttime view southwestward across a part of the Los Angeles basin from Mt. Wilson, 1950, showing elongate structural highs that trend northwestward as dark areas across the basin floor. Repetto Hills, parts of the Newport-Inglewood uplift, San Pedro Hills, and Catalina Island appear at successively greater distances in left-hand part of view, and the Baldwin Hills, which mark a more northwesterly part of the Newport-Inglewood uplift, are in right-center distance. *Photo courtesy of William C. Miller.*

F. J. H. Merrill, C. R. Orcutt, W. L. Watts, and several others. During the last quarter of the century, teachers and students from the University of California and Stanford University also contributed vigorously to the growing total of geological information. Joseph Le Conte, J. C. Branner, A. C. Lawson, J. C. Merriam, and J. P. Smith were among the leaders in this early work, in which attention was directed mainly toward geologic mapping and to stratigraphic, structural, mineralogic, and paleontologic studies.

Period of Intensive Geologic Investigations. The first half of the present century was a period of burgeoning population in southern California, especially in the coastal areas. From a city of about 100,000 persons, Los Angeles grew to a sprawling metropolis with a population of nearly 2,000,000 (figs. 1, 2), and the population of San Diego multiplied nearly 120-fold. Accompanying this remarkable growth were further expansion of agricultural activities and an impressive development of many industries. In a very fundamental way, these and other major trends affected the amount and the kinds of geological work that was done in the region.

A long-term dwindling of interest and activities in metal mining was overshadowed by rapidly increasing demands for petroleum and many of the industrial minerals. By 1948, when the annual value of mineral production in the State reached the billion-dollar level, nonmetallic commodities accounted for more than 95 percent of this total. Discoveries of new reserves of oil and gas were reflected in production rates that increased from a modest average of 12,000 barrels per day in 1900 to averages of 850,000 barrels per day in 1923 and 982,000 barrels per day in 1952. The value of petroleum and petroleum products, obtained chiefly from fields in southern California, was approximately $975 million in 1952, but even this output was not sufficient to meet all demands in the region. Similar production trends characterized many of southern California's industrial minerals, although in general the periods of maximum increase came at later times.

Geologic knowledge was applied directly to the search for oil and gas beginning about at the turn of the century, and within a few years detailed studies of stratigraphy and structure led to discovery and development of new fields, as well as to improved understanding of fields that had been found earlier on the basis of surface seepages. The general trend of investigations in petroleum geology is clearly shown in the published record, as the earlier and largely descriptive summary reports (e.g., Goodyear, 1888; Eldridge, 1903) were followed by a long series of detailed reports, mainly by members of the U. S. Geological Survey, outlining the results of intensive studies in specific areas and districts (e.g., Eldridge and Arnold, 1907; Arnold and Anderson, 1910; Arnold and Johnson, 1910; Pack, 1920; English, 1921, 1926; Kew, 1924; Hoots, 1931; Woodring, et al., 1932, 1940). The work of these men, and of numerous oil-company geologists, members of university staffs, and other investigators, provided a sound basis for further interpretations, as well as for the pursuit of many specific lines of investigation in large parts of the region.

The geologic study of several other nonmetallic materials, particularly the salines, evolved in a similar way, and intensive investigations have continued to the present time, especially in the interior parts of the region. The earlier work of many geologists (e.g., Gale, 1914, 1915, 1926; Hess, 1908, 1910; Noble and Mansfield, 1922; Noble, 1926, 1931; Schaller, 1930) not only outlined the major features of numerous widely distributed deposits, but yielded more general data that, combined with the results of several broad reconnaissances (e.g., Ball, 1907; Knopf, 1918; Ellis and Lee, 1919; Brown, 1923; Thompson, 1929), formed the necessary background for later detailed studies. Of similar broad value were several other investigations that dealt in large part with metalliferous deposits (e.g., Harder, 1912; Hewett, 1931, 1954).

Beginning with those early days when the modest needs of the pueblo of Los Angeles were met by the Zanja Madre, or "Mother Ditch," and when streams and shallow wells supplied other settlements, the development of southern California's water resources was marked by a steadily expanding search for underground supplies. As the country became more populous, many of these supplies were found to be less than adequate, and the year 1913 marked the beginning of large-scale importations of water into some areas. In the meantime, geologic and hydrologic studies of both surface and underground supplies were made by the U. S. Geological Survey (e.g., Schuyler, 1896-1897; Mendenhall, 1905, 1908, 1909; Lee, 1912; Waring, 1919, 1921), and in later years by other organizations, as well. During recent decades, problems of water budgeting, natural and artificial recharge, and contamination have been added to those of water occurrence, and some of the latest studies of these problems have involved impressive syntheses of stratigraphic, structural, and geochemical data (e.g., Eckis, 1934; Upson, 1951; Piper, et al., 1953).

Residents of southern California have been painfully aware of earthquakes and related phenomena since the days of earliest settlement, and for more than fifty years the relations between earthquakes and faults in the region have received geological attention. From the times when features that were formed along the trace of the San Andreas fault by the Fort Tejon shock of 1857 were described by Schuyler (1896-1897, pp. 711-713) and Fairbanks (Lawson, et al., 1908, pp. 43-45), attempts have been made to analyse southern California earthquakes in terms of their geologic causes and effects, and to solve the exceedingly difficult problem of earthquake prediction. The distribution, timing, and nature of fault movements and the elastic waves generated by them have been studied by means of increasingly detailed field observations, geodetic investigations, and the recording and analysis of seismic data obtained with a growing variety of instruments. The recent Arvin-Tehachapi (Kern County) earthquake in the southern end of the San Joaquin Valley (Benioff, et al., 1952; Buwalda and St. Amand, 1952) involved a series of shocks that probably has been more thoroughly and accurately recorded than any other in history, and a summary report on this earthquake is in press (1954) as Bulletin 171 of the State Division of Mines.

The value of geologic knowledge as applied to the location, design, and construction of engineering works has been increasingly recognized in southern California during recent years. The collapse of the St. Francis dam and its tragic consequences (Ransome, 1928), the effects of numerous floods (e.g., McGlashan and Ebert, 1918; Troxell and Peterson, 1937; Troxell, et al., 1942) and earthquakes (see Richter, Contribution 1, Chapter X, this volume), and the more commonly recurring damage from landslides, subsidence, and other earth movements have prompted geologic investigations of many kinds.

The research activities of members of university staffs and many other investigators have spanned a host of problems, especially during recent decades, and a few have led to the mapping of large areas (e.g., Larsen, 1948; Dibblee, 1950). Some, in contrast, have involved much time in the laboratory, and have included paleontological, geophysical, and geochemical work. As these and the numerous other investigations in the region have become increasingly diversified in their nature and aims, and as the investigators themselves have represented a growing variety of interests and affiliations, attempts have been made to summarize the existing information and, in some instances, to make tentative interpretations. One of these attempts produced a summary of geologic features and their relations to earthquakes (Hill, 1928), and another yielded a useful guidebook that was published under the auspices of the U. S. Geological Survey (Gale, et al., 1932) for the Sixteenth International Geological Congress. Others, devoted mainly to the geology of the stratified rocks, resulted in publication of the classic volumes by Reed (1933), Reed and Hollister (1936), and Jenkins, et al. (1943). An excellent geologic map of the entire State was prepared by the State Division of Mines in 1938 (Jenkins, 1938), and currently is undergoing fundamental revision on the basis of newly available information. Data on minerals of the State have been assembled by Murdoch and Webb (1948), on mineral deposits by the staff of the State Division of Mines (1950), and on geomorphic features by Hinds (1952).

THE NATURAL PROVINCES

Southern California is a region of great topographic and geologic diversity. Included within its limits are high mountain ranges (figs. 8, 11) and valleys whose floors lie below sea level (fig. 5), precipitous canyons and broad basins at many levels (figs. 6, 8), and an assemblage of other physiographic features that reflect a complex geologic history and a wide variety of rock types and structural elements. The land of the region is readily divisible into eight natural provinces, in large part on the basis of distinctive physiographic characteristics, but more fundamentally on the basis of geologic history since middle Mesozoic time.

The physical divisions of southern California already have been described by Hill (1928, pp. 74-101), Fenneman (1931, pp. 373-379, 493-508), Reed (1933, pp. 1-26), Jenkins (1938), Hinds (1952, pp. 63-108, 145-229), and several others, and hence only a brief summary of outstanding geologic features is presented in the following paragraphs. The distribution, areal dimensions, and major topographic elements of the provinces are shown in figures 3 and 4.

Southern Coast Ranges. The southern part of the Coast Range province is characterized by a topographic and structural grain that trends northwest to north-northwest. A thick section of upper Mesozoic and Cenozoic sedimentary rocks, mainly marine and mainly clastic, is exposed over most of the area. These strata rest upon, or are in fault contact with, mildly metamorphosed but intricately deformed rocks of the Jurassic (?) Franciscan group, which include sandstone, conglomerate, shale, chert, limestone, various schists, basalt, diabase, and associated basic intrusive rocks that have been largely altered to serpentine.

The province is sliced almost longitudinally by two major fault zones, the San Andreas on the northeast and the Nacimiento on the southwest (fig. 12), as well as by many other subparallel breaks with northwesterly trend. Partly exposed in the block between the two main faults is a core of plutonic rocks, chiefly quartz diorite and granodiorite of probably Mesozoic age. This block appears to have been a highland mass during much of Tertiary time, while sediments were being deposited in the flanking areas. Tertiary deformation, especially in middle Miocene, upper Pliocene, and mid-Pleistocene times, is reflected by numerous folds, faults, and unconformities in the sedimentary section.

San Joaquin Valley. The San Joaquin Valley, or southern part of the Great Valley of California, is an immense, nearly flat-floored plain that is largely covered by alluvium. It was an important basin of Cenozoic deposition, and beneath its floor is a remarkably thick

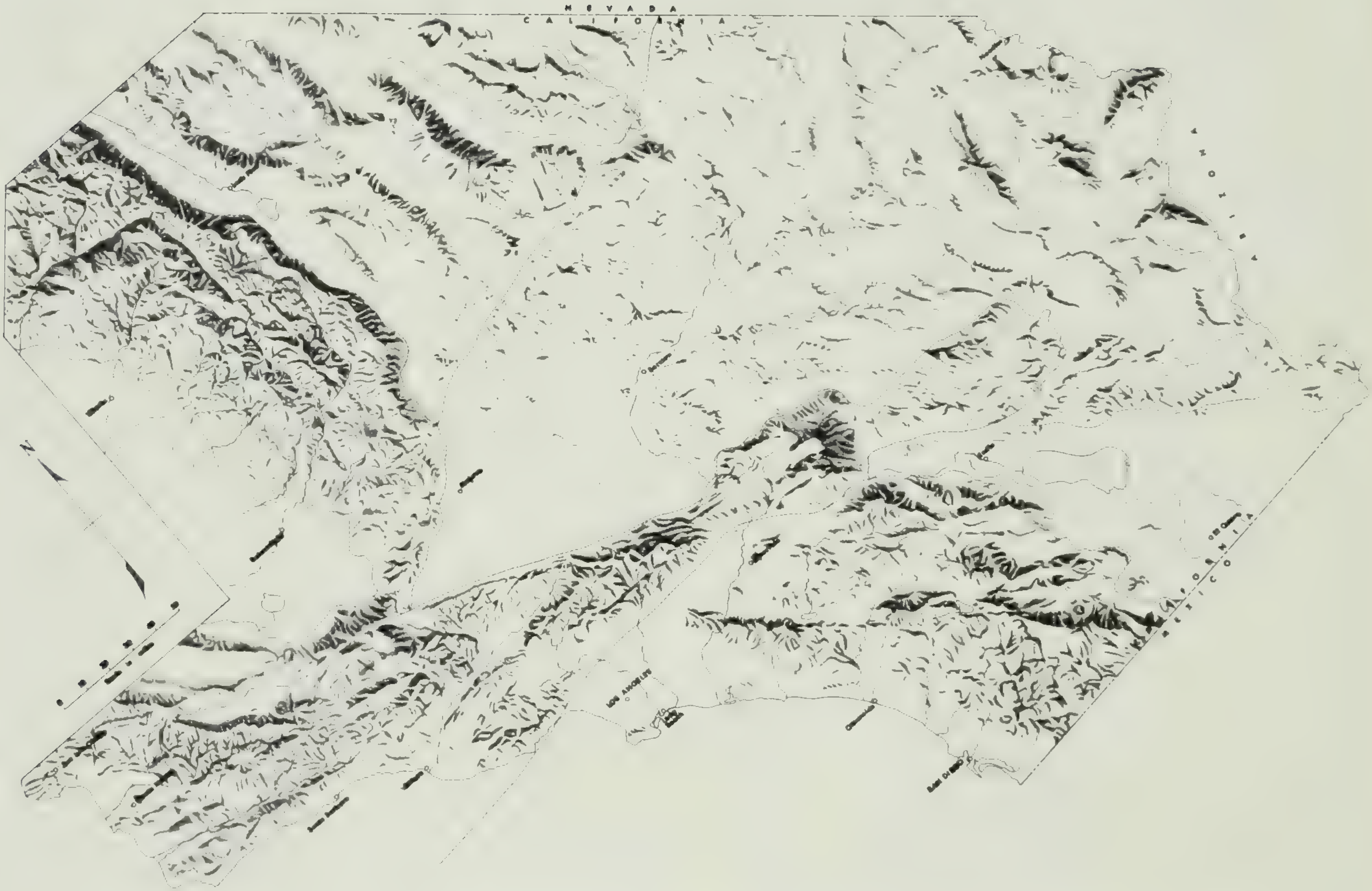

FIGURE 3. Map showing the major topographic features of southern California. Dashed lines are generalized boundaries of the natural provinces.

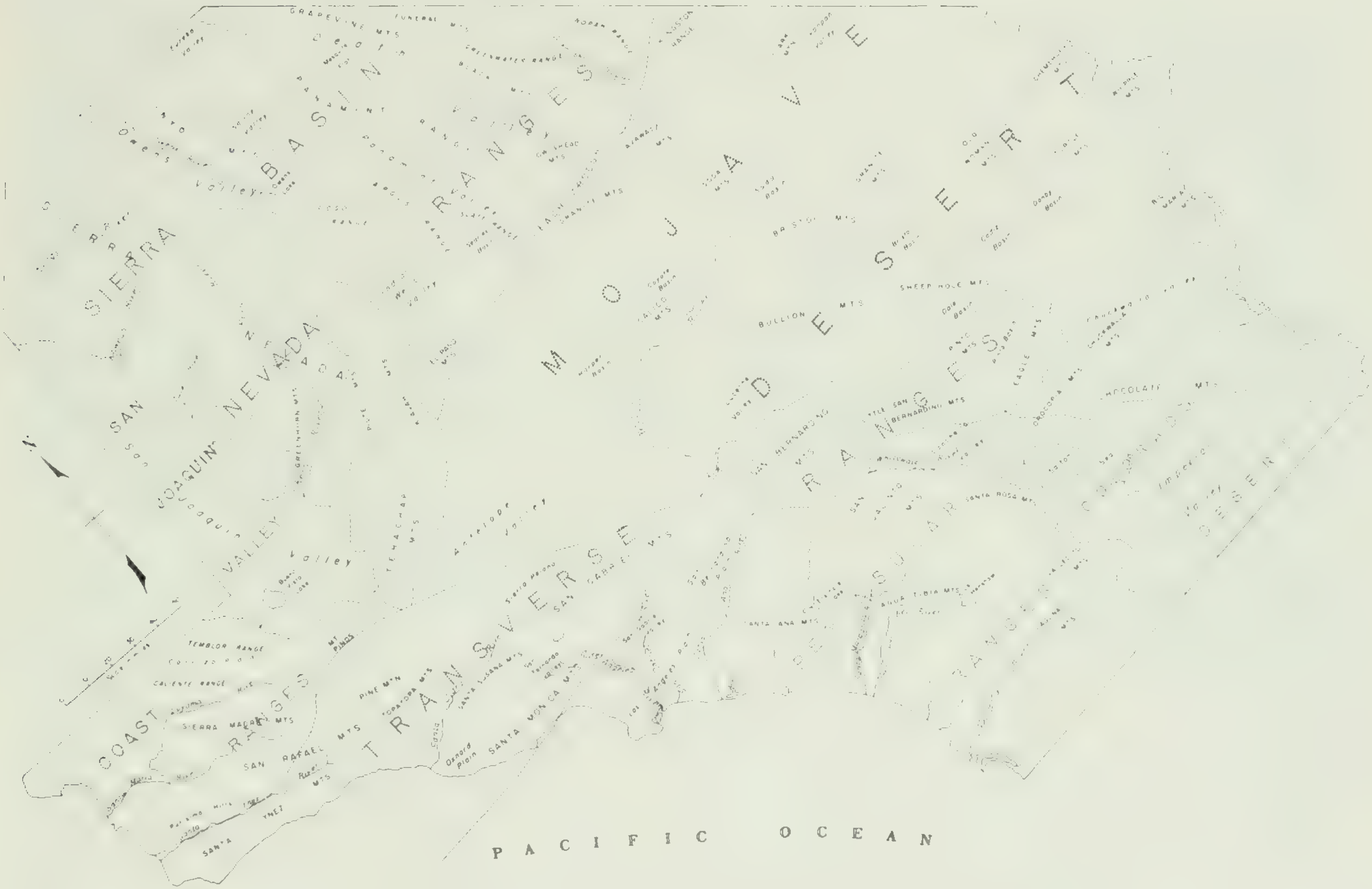

FIGURE 4. Map showing the natural provinces of southern California, with names of the principal features shown in figure 3.

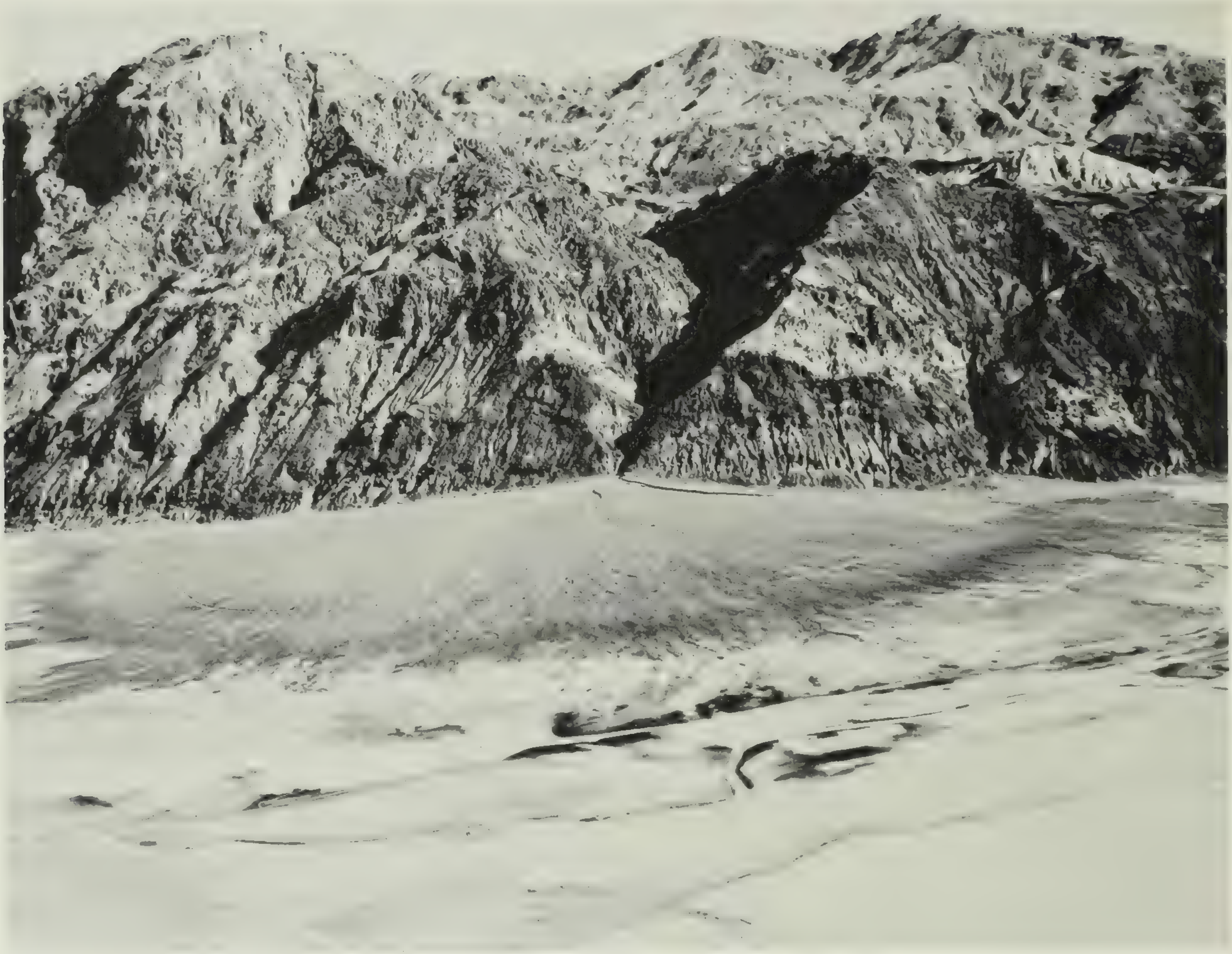

FIGURE 5. View eastward at the steep, fresh fault scarp of the Black Mountains, with the floor of Death Valley in foreground. The strikingly symmetrical alluvial fan heads at the mouth of Coffin Canyon, an extremely narrow and precipitous gorge that gives way upstream into somewhat more open country. *Photo by J. S. Shelton and R. C. Frampton.*

and varied section of dominantly clastic sedimentary rocks. More than 25,000 feet of Upper Cretaceous marine strata is overlain by as much as 40,000 feet of younger formations that include both marine and nonmarine strata, as well as some volcanic rocks of basic and intermediate composition.

The broad trough of sedimentary deposits is asymmetric, with a relatively steep westerly flank and a gently inclined easterly flank that lies upon the western part of the Sierra Nevada fault block. During much of Tertiary time this basin was occupied by an inland sea, and a variety of lithologic facies accumulated contemporaneously as its floor continued to subside (Hoots, et al., Contribution 8, Chapter II, this volume). Several episodes of uplift and depression are attested by unconformities and by lithologic contrasts within the sedimentary section, and many open folds, developed chiefly in mid-Pleistocene time, are present in both the marginal and interior parts of the basin. Several prominent lines of folding project southeastward and east-southeastward into the valley from its western margin, and relatively severe deformation in the southern end and along the western side of the valley is expressed by numerous thrust faults and overturned sections of stratified rocks.

Sierra Nevada. The southern part of the Sierra Nevada proper is fundamentally a huge, asymmetric, westward-tilted block that is bounded on the east by a zone of high-angle faulting and disappears to the west beneath the sedimentary rocks of the San Joaquin Valley. This block consists mainly of plutonic rocks that represent the composite Sierra Nevada batholith of Mesozoic age, together with older metamorphic rocks that appear in most areas as inclusions, roof pendants, and screens in the igneous terrane. Resting upon these crystalline rocks are scattered patches of lower Tertiary fluviatile sediments, as well as Tertiary and Quaternary volcanic rocks. Pleistocene glaciation has left its stamp on the landscape within the range, and glacial deposits are widespread.

The Tehachapi Mountains, at the south end of the province, differ from the Sierra Nevada proper in several important respects. Although they consist mainly of the same kinds of pre-Cenozoic rocks, they trend northeast, are bounded on both sides by major fault zones, and appear to have a much more complex internal structure. Within the range are large masses of Tertiary nonmarine strata and associated volcanic rocks, and along its margins are moderately to steeply tilted sections of Tertiary rocks. Both the Tehachapi Mountains and the Sierra Nevada appear to have been affected by several episodes of uplift during Cenozoic time, and the most recent and possibly greatest of these took place in Pleistocene time.

Basin-Range Province. The part of the Basin-Range province that lies in southern California is characterized by north-trending ranges, intervening valleys and basins, and an interior drainage. The geologic section is very complex, and includes earlier pre-Cambrian gneisses and plutonic rocks; several thousands of feet of younger pre-Cambrian sedimentary rocks and diabase; as much as 17,000 feet of clastic and carbonate strata of Cambrian age; assemblages of younger Paleozoic strata, of even greater aggregate thickness, in which carbonate rocks are abundant; Mesozoic sedimentary and volcanic rocks; widespread plutonic rocks of Mesozoic age; fluviatile and lacustrine sedimentary strata that appear to have been deposited during various parts of the Cenozoic era, mainly in separate basins; and widely scattered volcanic and intrusive rocks of Cenozoic age. Not all of these rocks ordinarily are present in any single area.

Many of the ranges are essentially fault blocks, and some of the valleys are fault-bounded troughs, but neither the structural pattern nor the history of deformation in the region is at all simple. Indeed, adjacent fault blocks commonly have had distinctly different geologic histories, thanks mainly to the nature and timing of movements on the faults that separate them. The province is in part bounded on the south by the Garlock fault zone (fig. 7), along which there has been much left-lateral movement, and it is bounded on the west by the Sierra Nevada fault zone, along which dip-slip movement probably has been dominant. Within the province are many other high-angle faults, as well as flat to moderately-dipping thrust faults, and in general faulting has been the dominant expression of tectonic activity.

The effects of late Mesozoic and Cenozoic deformation are exposed in most parts of the region, and widespread Quaternary faulting and warping is reflected by many elements of the present topography. Impressively fresh fault scarps (fig. 5), scarplets and small grabens in alluvial-fan deposits (fig. 6), aligned ridges and trenches on several valley floors (fig. 7), and hogback ridges of tilted and folded Pleistocene deposits are typical examples. Also preserved in several of the basins are shoreline and outlet features of Pleistocene and early Recent lakes (fig. 7) that at least once were parts of an integrated system of drainage.

Mojave Desert. The Mojave Desert region, most extensive of the natural provinces, is in large part a gigantic fault-bounded wedge that points westward. It consists of pre-Cambrian gneisses, plutonic rocks, and severely deformed and metamorphosed sedimentary rocks; sections of Paleozoic stratified rocks that have been metamorphosed to various degrees; scattered sedimentary, metasedimentary, and metavolcanic rocks of Mesozoic age; a considerable abundance and variety of Mesozoic intrusive rocks; and middle and upper Cenozoic

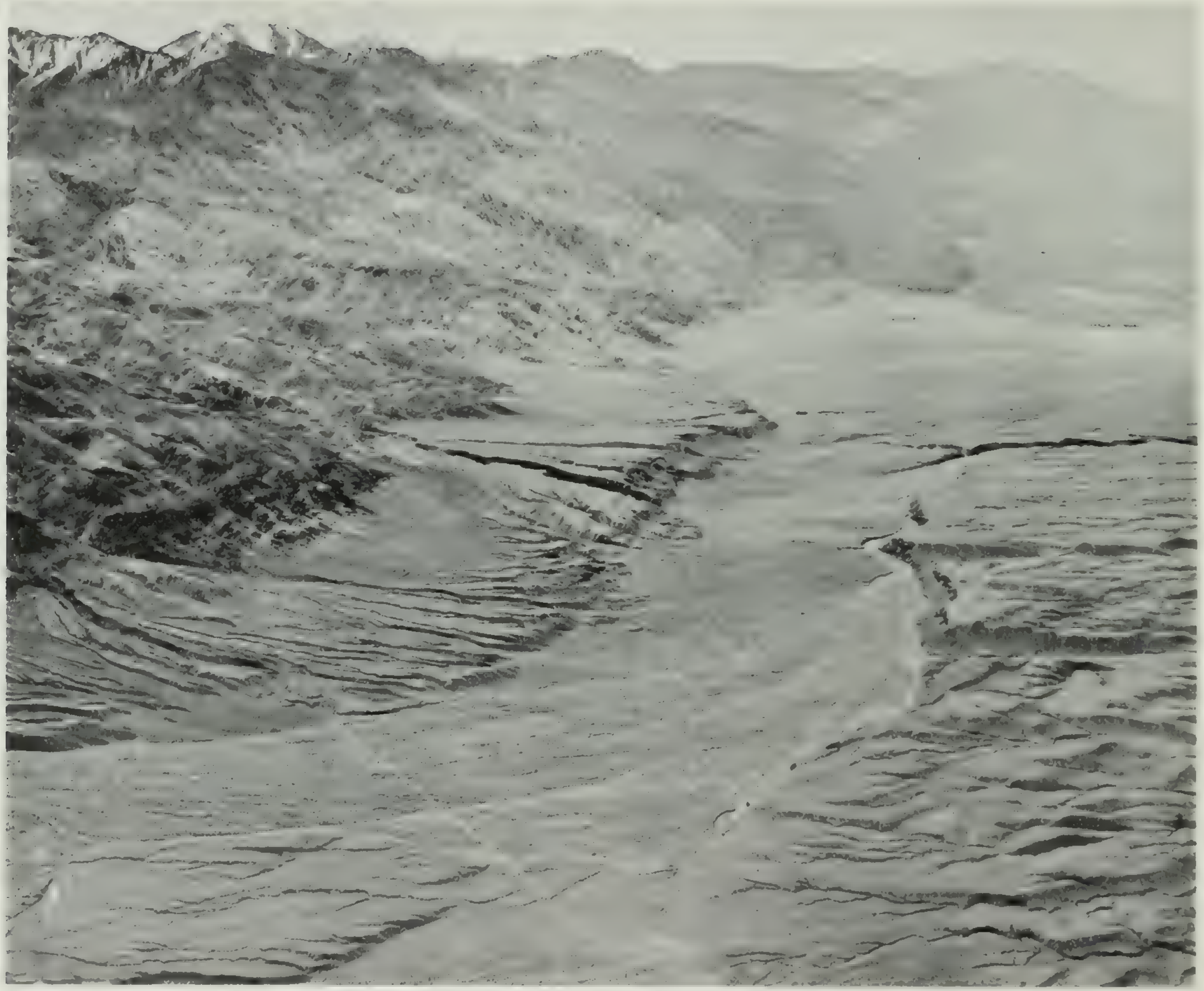

FIGURE 6. The Wildrose graben and a part of the Panamint Range, as viewed south-southeastward from a point above Panamint Valley. The graben was developed across a series of Quaternary alluvial fans, and beheaded much of the drainage in the area at right. Much of the visible mountain area is underlain by stratified rocks of Cambrian and pre-Cambrian age. *Photo by J. S. Shelton and R. C. Frampton.*

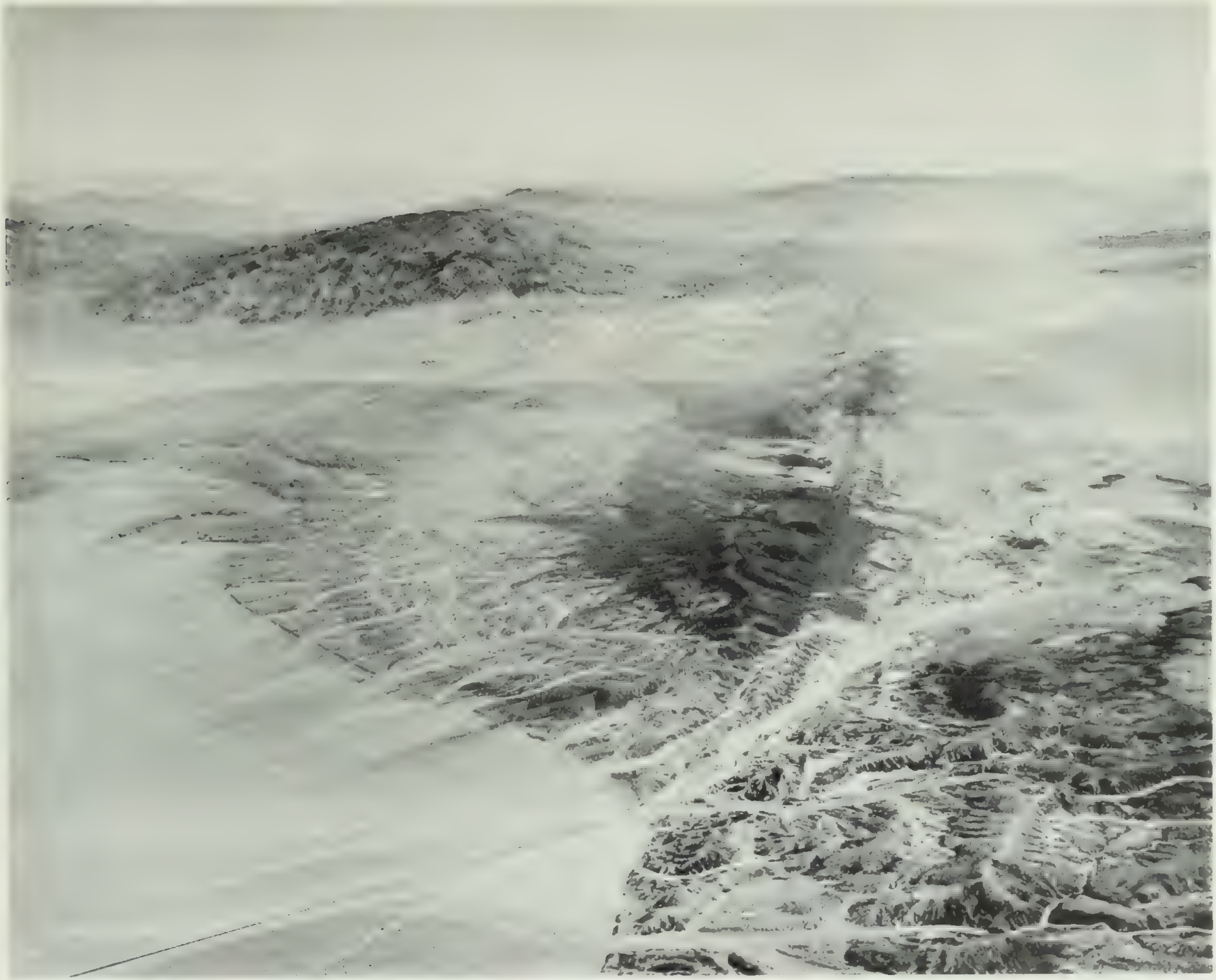

FIGURE 7. The Garlock fault zone, as viewed east-northeastward from a point over the southwestern corner of the Searles Basin. Note the fresh scarps and the elongate trench, the deepest part of which is marked by a small playa. Shoreline features of a lake that occupied the Searles Basin during a part of Pleistocene time are clearly visible in left foreground. The Slate Range is in near distance, and in extreme distance beyond is Charleston Peak, in Nevada. *Photo by J. S. Shelton and R. C. Frampton.*

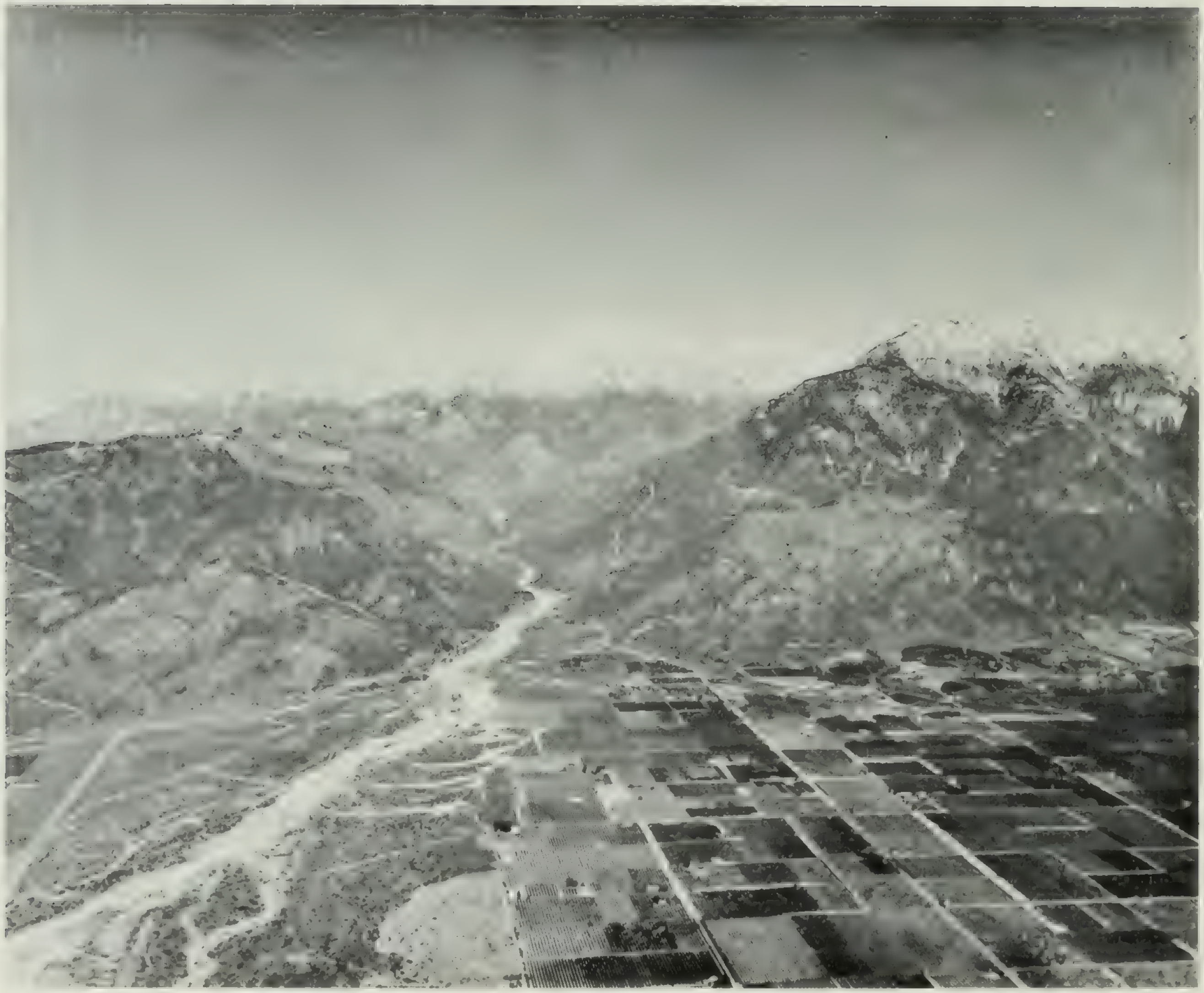

FIGURE 8. View northward at the bold south face of the San Gabriel Mountains, here interrupted by San Antonio Canyon. San Antonio Peak is in distance, and Ontario Peak is nearer and at right. *Pacific Air Industries photo.*

igneous rocks and sedimentary strata that were deposited mainly in separate basins.

Younger pre-Cambrian sedimentary rocks like those in the Basin-Range region to the north have been recognized only in the northern corner of the Mojave Desert province. No lower Paleozoic strata have been identified in the central and western parts of the province, although they may be present as metamorphic rocks in some areas. In general, fossiliferous sections of unmetamorphosed pre-Cenozoic rocks are common in the northeastern part of the region only, and with few exceptions the stratigraphic relations become progressively more obscure to the west and south. The province was subjected to widespread erosion from late Mesozoic to middle Tertiary time, and, unlike the regions to the north, south, and west, it contains no Lower Tertiary sedimentary rocks (Hewett, Contribution 1, Chapter II). Younger fluviatile and lacustrine sediments indicate a complex history of basin formation that began in middle Miocene time and continued to the present.

Much of the province lies between the left-lateral Garlock fault on the north and the right-lateral San Andreas fault on the southwest (fig. 12). Within the province are north- to northeast-trending folds, steeply dipping faults, and some major thrust faults of middle Jurassic to late Cretaceous age, as well as more open folds, low-angle thrust faults, and steeply dipping faults of late Cenozoic age. Many of the high-angle faults trend northwest (fig. 12) and show evidence of recent movement. Igneous activity in the region is represented mainly by pre-Cambrian and Mesozoic plutonic rocks, pre-Cenozoic volcanic and metavolcanic rocks, and Cenozoic volcanic and hypabyssal intrusive rocks.

Transverse Range Province. Trending essentially east-west across the regional grain of southern California is the Transverse Range province, which comprises elongate mountain ranges and valleys, chains of hills, and broad basins that are geologically very complex. Its eastern half, which includes much high and mountainous country (figs. 8, 11), is composed mainly of Mesozoic plutonic rocks, older metamorphosed sedimentary and volcanic rocks that are at least in part of Paleozoic age, and some igneous and metamorphic rocks of pre-Cambrian age. Tertiary sedimentary rocks, both nonmarine and marine, are preserved locally. The western half of the province is featured by diverse sections of Tertiary sedimentary rocks, in places enormously thick, that were deposited in several large basins (fig. 9). These and associated volcanic rocks rest upon and against older sedimentary rocks, as well as still older crystalline rocks that are in part correlative with those exposed in areas farther east.

The province as a whole resembles the adjoining Coast Range and Peninsular Range regions in several respects, but is distinguished from them by prevailing east-west structural trends. Elongate, generally steep-sided folds, many of which have been ruptured along their axes or on one or both flanks by gently to steeply dipping compressional faults, are characteristic of the basinal areas and those western ranges that consist mainly of sedimentary rocks (fig. 9). The other ranges are best regarded as great upthrown blocks, bounded in part by faults that dip very steeply and have had large strike-slip, or lateral, components of movement, and in larger part by reverse faults that appear to converge downward beneath the blocks. The great San Andreas-San Jacinto fault zone slices across the eastern part of the province at an acute angle, and the San Gabriel fault zone is somewhat similarly disposed farther west (fig. 12).

Several episodes of intense deformation, including a late Mesozoic orogeny and accompanying widespread plutonic intrusion, are recorded by the older rocks. The Cenozoic section contains unconformities, some of them extensive, that reflect a variety of disturbances in both basin and source areas. The great mid-Pleistocene orogeny produced intense folding and uplift, and was responsible for development of the major elements of the present topography, including a number of impressive scarps (fig. 8). Marine terraces of Pleistocene age are prominent features of the coastal landscape, and lie at elevations of as much as 1,200 feet above sea level. Some of them have been warped and broken by faults.

Colorado Desert. The Colorado Desert is an elongate, low-lying depression whose alluviated floor is separated from the Gulf of California by the delta of the Colorado River and is in part occupied by the Salton Sea. It marks the site of a former basin of middle and late Cenozoic sedimentation, and a thick section of fine- to very coarse-grained, dominantly nonmarine strata, together with some volcanic rocks, is exposed in its marginal parts. This section rests upon igneous and metamorphic rocks of pre-Cenozoic age in some areas, and is in fault contact with them in others. The northeast side of the province is traversed longitudinally by several subparallel breaks of the San Andreas fault zone, and its highly irregular western margin is in part outlined by the Elsinore, San Jacinto, and other major fault zones that trend northwest (fig. 12). Many of the faults cut and offset rocks that are as young as Quaternary.

Most of the sedimentary rocks were laid down as alluvial-fan and lacustrine deposits, but included in the sequence are marine beds that accumulated in a shallow, northward-extending arm of the Gulf of California during lower Pliocene time. The most recent history of the basin involves subsidence, local volcanic activity, intermittent movements along faults in both the marginal and interior areas, and occupation by at least one large fresh-water lake, perhaps as recently as a few hundred years ago.

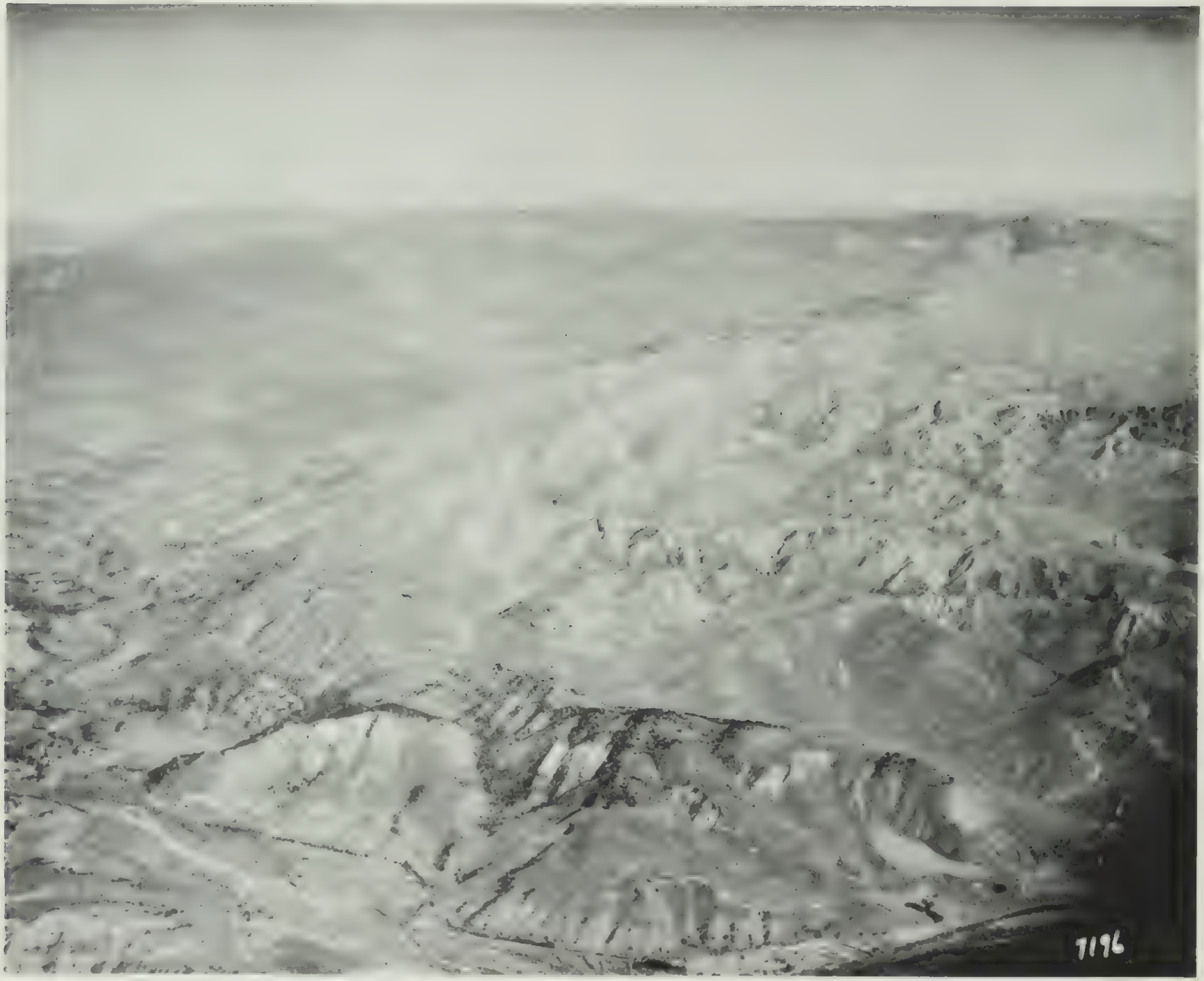

FIGURE 9. The Ventura River Valley, Ojai Valley, and adjacent mountains, viewed northeastward from a point about 6 miles north of Ventura. A thick section of Miocene and Pliocene strata is exposed in the Ventura Hills and on Sulphur Mountain, in foreground and central part of view, respectively. Eocene strata are prominent on the face of the Topatopa Mountains, in distance beyond Ojai Valley, and older rocks form most of the mountains in far distance. *Photo by Erickson, 1931.*

Peninsular Range Province. The Peninsular Range province is characterized by a northwest-trending topographic and structural grain that butts abruptly against the Transverse-Range grain on the north. The inland parts of the province include several high mountain ranges (figs. 10, 11), and are underlain chiefly by igneous, metasedimentary, and metavolcanic rocks of Paleozoic and Mesozoic age. The igneous rocks include widespread representatives of the great composite southern California batholith. Patches of younger volcanic rocks and nonmarine sediments of middle and late Cenozoic age are present locally.

A coastal plain of irregular outline is marked by numerous marine terraces. It is underlain by dominantly clastic marine and nonmarine strata of Upper Cretaceous, Tertiary, and Quaternary age, as well as by scattered volcanic rocks of Tertiary and Quaternary age. This section thickens to as much as 40,000 feet in the Los Angeles basin (fig. 10), at the north end of the province, where it evidently accumulated in a subsiding area under widely varying conditions of sedimentation. In many respects this basin resembles other Tertiary basins in the adjoining Transverse Range province, but its major structural features have the characteristic Peninsular Range trend.

The offshore area, or continental borderland, commonly is included in the Peninsular Range province. It is distinguished by prominent, steep-sided ridges that appear to be horst-like in structure, and by intervening depressions that in general have the form of closed basins (Emery, Contribution 7, Chapter II). The ridges are composed mainly of foliated rocks that resemble the Franciscan formation of the Coast Ranges to the northwest, and in places are covered with sedimentary and volcanic rocks of Tertiary age. Younger sediment also veneers the ridges, and forms considerable thicknesses of fill in the basins.

The entire province can be regarded as an uplifted and westward tilted plateau that has been broken into several large, elongate, subparallel blocks by major faults that trend northwest (fig. 12). Most of these faults have been intermittently active during large parts of Cenozoic time, and adjacent fault blocks commonly have had distinctly different histories. The sedimentary sections have been folded along axes that trend west-northwest to north-northwest. Most of the large folds are open, with undulatory crests and troughs that in some areas have affected the accumulation of oil (fig. 10), and many are complicated by unconformities and small-scale wrinkling. Some of those in the Los Angeles basin were developed so recently that their distribution and form are plainly reflected by the present topography (figs. 2, 10).

CURRENT GEOLOGIC PROBLEMS

In the preface to his volume on the geology of California, Reed (1933, p. VII) pointed out the need for increased consideration of broad problems with the following apt remarks:

> "The last thirty years have thus contributed a supply of accurate data of the type needed for an adequate interpretation of the problems of regional geology and geologic history. During this period, however, relatively less attention than formerly has been given to the broader aspects of these problems. California geology has thus come to seem more complex, disconnected, and chaotic than ever before. In recent years some geologists have even entertained the idea that the State is really nothing but a great series of separate structural blocks, each with an independent history since some stage of the Mesozoic at least. The adoption of any such hypothesis would apparently make hopeless an attempt to write an account of regional geology or general geologic history. In order to keep this disintegrative tendency within bounds, and also to see the problems of special districts in their broader relations, there seems to be a need for attempted synthesis like that presented in this paper."

That many geologists are aware of a renewed need for summation and synthesis of available data is implicit in the preparation and publication of the present volume. Even though the ''disintegrative tendency'' of 20 years ago may have been more apparent than real, the theme of adjacent fault blocks with contrasting—albeit neither independent nor unrelated—histories is founded upon such widespread and compelling evidence that it cannot be ignored. It poses some formidable problems of correlation and integration, to be sure, but their solution will be fundamental to ultimate elucidation of southern California's geologic history.

Many of the problems that are discussed in the following contributions to this volume are common to more than one fault block or to more than one general province, and some of them are treated on a regional basis in at least 21 of the contributions. The ratio of known questions to wholly satisfactory answers still is provokingly high, but the outlook for its net reduction seems to be far from discouraging. A brief and incomplete sampling of current problems, not including solutions thereto, is presented in the remainder of this paper.

Pattern of Major Faults. As fault maps of southern California are improved in the light of new data, and as the significant elements of the pattern are more fully recognized, attempts to interpret these elements in genetic terms are still confronted by the need for additional information on the nature and timing of fault displacements, and on the directions and amounts of net slip. These factors are difficult to determine under any but the most favorable conditions, and the problem is compounded by evidence of reoriented movements along numerous recurrent faults.

The compilation in figure 12 shows most of the known major faults in a large part of southern California. Nearly all of these have been active during parts of Cenozoic time, and some date back at least to

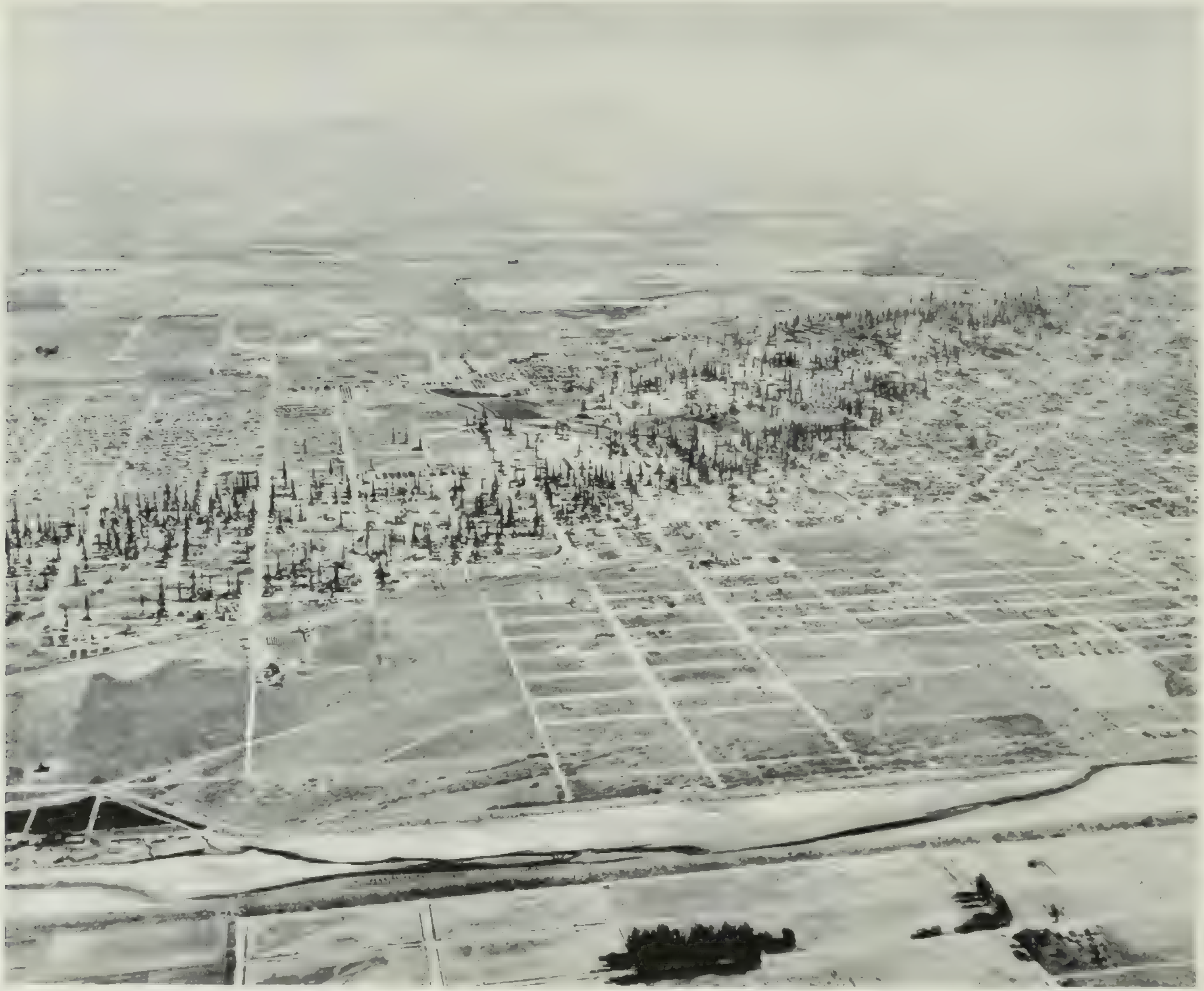

FIGURE 10. View eastward across a part of the Los Angeles basin, showing the Long Beach oil field as it appeared in 1932. The field marks the general position of the Newport-Inglewood uplift in this area. Signal Hill is at right, in the more distant part of the field, and Santiago Peak, in the Santa Ana Mountains, is at center on the skyline. *Photo courtesy Fairchild Aerial Surveys, Inc.*

mid-Mesozoic time. Especially prominent among them are the San Andreas, Garlock, Nacimiento, San Gabriel, San Jacinto, and Elsinore faults, all steeply dipping, deep-rooted, long-active breaks on which strike-slip, or lateral, movements amounting to miles or even tens of miles have taken place. These major breaks pose several problems that are discussed in Chapter IV and elsewhere in the published record (e.g., Crowell, 1952; Hill and Dibblee, 1953; Noble, 1954; Wallace, 1949), and it is interesting to note that, even for the faults that have been studied in painstaking detail, the most reliable estimates of net slip are based upon indirect evidence or upon a summation of several compatible lines of suggestive, but not conclusive, evidence. Only a few rock units or other features can yet be correlated with confidence across any of these faults, and unfortunately net slip rarely is measured by the separation indicated on a geologic map or section.

Thrust faults and high-angle reverse faults are common in the region southwest of the San Andreas fault, whereas major normal faults are very rare. In the country to the northeast, however, both normal and other types of dip-slip faults are present. Hill (Contribution 1, Chapter IV) has attempted to correlate the directions and amounts of displacement along the major lateral, reverse, and thrust faults with a primary pattern of deformation, and has thereby deduced a regional strain pattern of north-south shortening. Although admittedly over-simplified, especially with respect to timing of movements, this is an imaginative and stimulating application of the data now available. Hewett (Contribution 2, Chapter IV) has interpreted the regional pattern of faulting in the Mojave Desert province, and has performed a real service in correlating the fault movements with numerous other events in the geologic record.

The relations between the San Andreas fault system and the faults in structurally high parts of the Transverse Range province invite speculation on the history of movements. In the southern Coast Ranges the San Andreas fault zone is a relatively narrow and well-defined master break that trends southeast. It bends sharply eastward before reaching the area of junction with the Big Pine and Garlock faults, and thence cuts across the Transverse Ranges in an east-southeastward direction (fig. 12). Along the northern edge of the San Gabriel Mountains it splits into two major fault zones, the San Andreas and the San Jacinto. Farther eastward, along the south side of the San Bernardino Mountains, the San Andreas zone is involved in a complex way with east-trending faults of the Transverse Range system, as shown by Allen (Map Sheet No. 20), and it differs in several important respects from its more northwesterly segments. It seems probable that a substantial part of the total displacement along these more northwesterly segments is represented to the southeast by displacements along the San Jacinto fault zone.

The Elsinore fault zone, which lies on the southeastward projection of the Coast Range segment of the San Andreas fault zone, may well be related in a similar way. Perhaps the ancestral San Andreas fault was deflected eastward by the great mass of the Transverse Ranges, and some of its older segments were converted into parts of the reverse faults along which the Transverse Ranges were uplifted. The interplay of movements probably was very complex in both space and time, and the present San Andreas and San Jacinto fault zones almost certainly displaced many of the Transverse Range breaks. The many pieces of this puzzle are even more difficult to assemble than those in the area where the San Andreas and Garlock faults meet (Hill and Dibblee, 1953), and solution of the general problem must await detailed mapping and interpretation of the crystalline rocks in a very large area.

Deformation and Metamorphism of the Older Rocks. Most of the pre-Cretaceous rocks exposed in southern California show the effects of at least one episode of deformation and metamorphism that antedated the sequence of severe deformation recorded by many of the younger rocks. So complex are most of the end products, however, that few investigators have attempted to decipher their earlier structural history. Several of the principal difficulties of interpretation have been summarized for the Mojave Desert region by McCulloh (Contribution 2, Chapter VII), and the problems are still more troublesome in areas farther west and southwest, where the older geologic record is even less well known.

Pre-Tertiary thrust faulting is recorded from several areas (e.g., Hewett, 1931, pp. 42-55; Noble, Contribution 5, Chapter IV), and ancient folding and high-angle faulting have been noted from numerous areas in which the older rocks have been studied. Superimposed upon most of these features are the effects of younger deformation, which commonly include pervasive crushing, shearing, and even mylonitization. In some places massive crystalline rocks plainly have participated in the folding of overlying sedimentary strata (e.g., Hill, 1930, pp. 158-159; Dibblee, Contribution 2, Chapter II). Additional descriptive information, supplemented by careful studies of rock fabric and structure in relation to tectonic environment (e.g., Weiss, 1954), must be at hand before the more general aspects of deformation in the older rocks of the region can be satisfactorily determined.

The problems of metamorphism also are complex, mainly because of difficulties in establishing the nature and timing of individual metamorphic effects. Some of the rocks may well have been metamorphosed prior to widespread intrusion of the Mesozoic plutonic

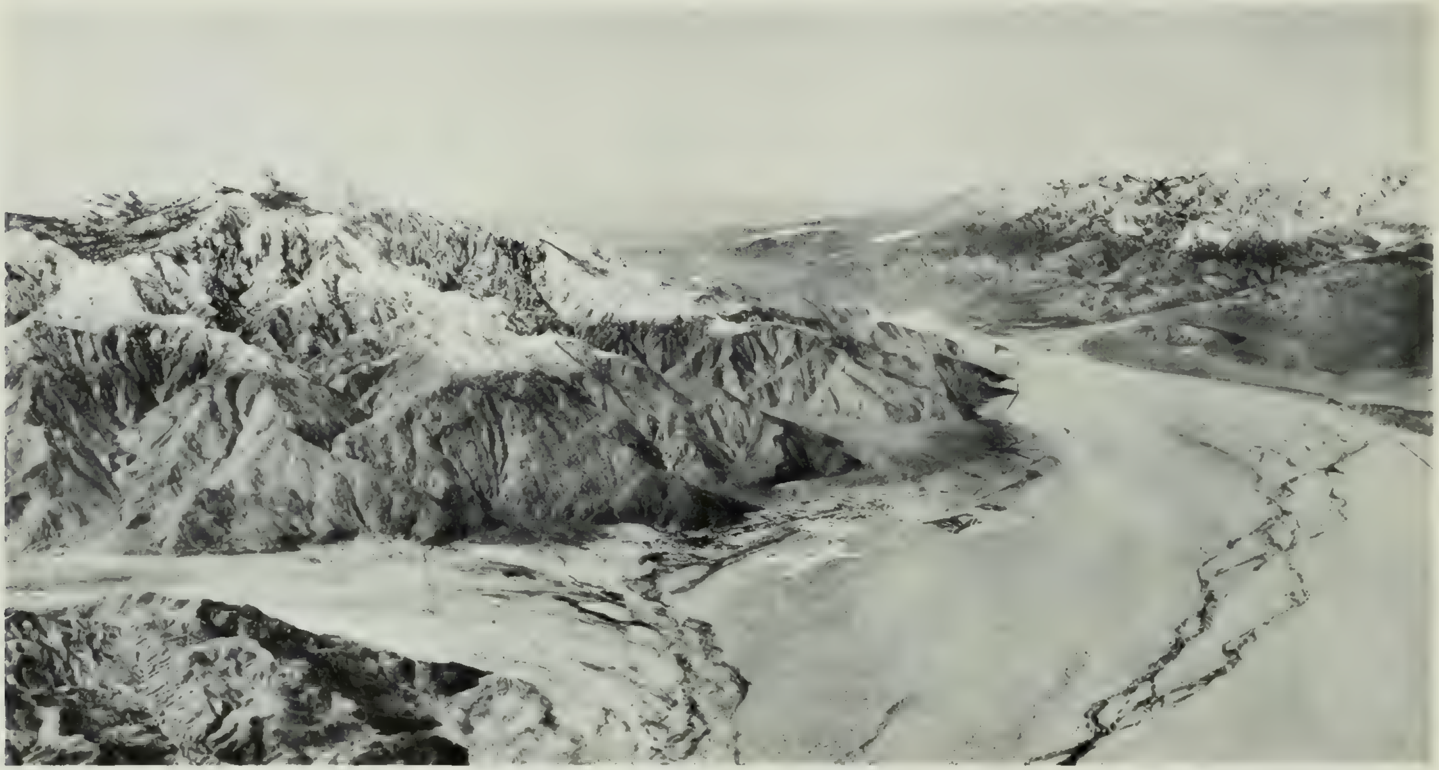

FIGURE 11. San Gorgonio Pass and the highest country in southern California, as viewed west-northwestward from the Coachella Valley in 1931. San Jacinto Peak (10,831 feet) is at left, San Gorgonio Mountain (11,485 feet) is at right, and San Antonio Peak (10,080 feet) is in center distance. These peaks represent the San Jacinto, San Bernardino, and San Gabriel Mountains, respectively. Palm Springs is in center foreground. *Photo courtesy Fairchild Aerial Surveys, Inc.*

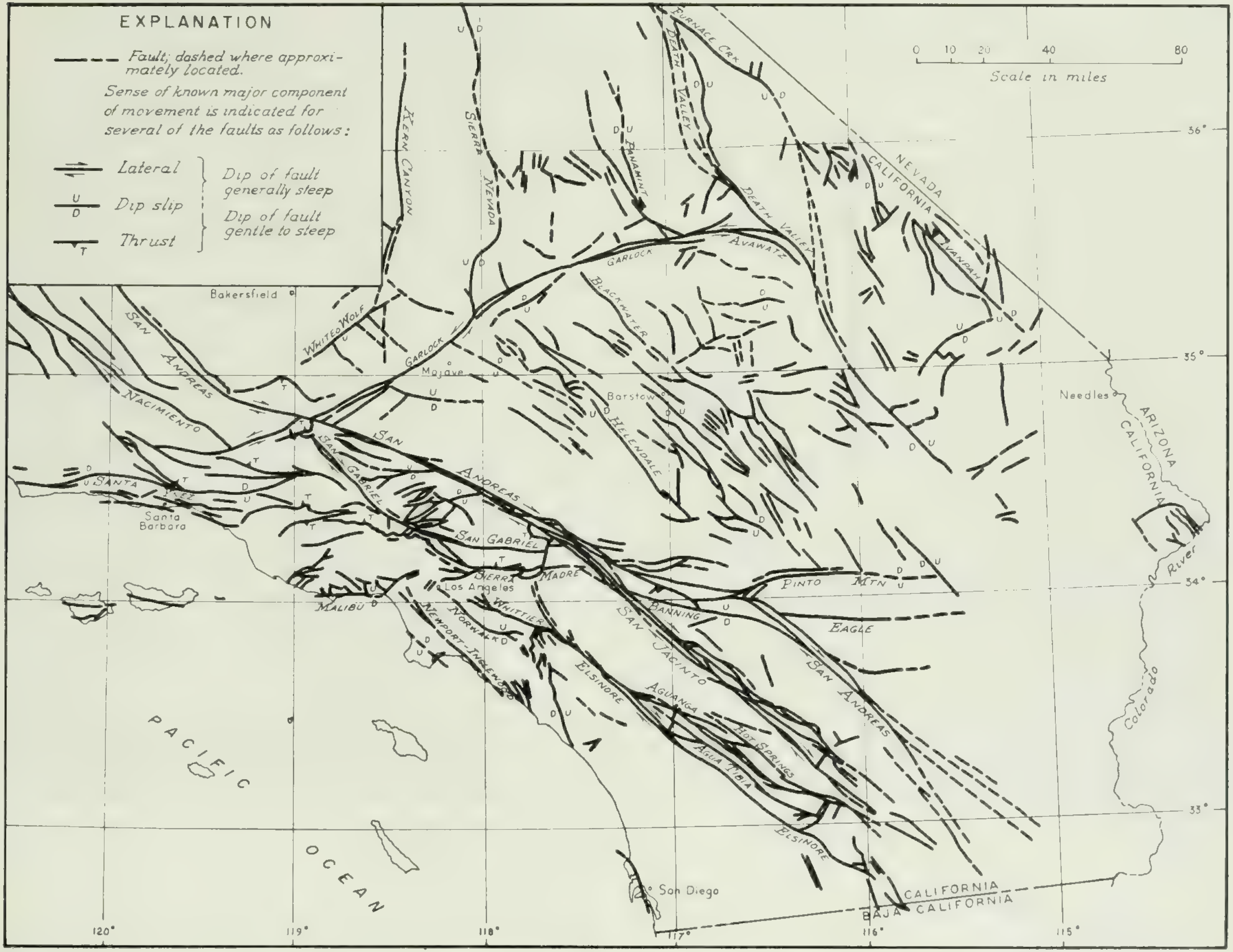

FIGURE 12. Map showing major faults in a large part of southern California. Based mainly on mapping and compilation by C. R. Allen, T. L. Bailey, T. W. Dibblee, Jr., D. F. Hewett, R. H. Jahns, and L. F. Noble.

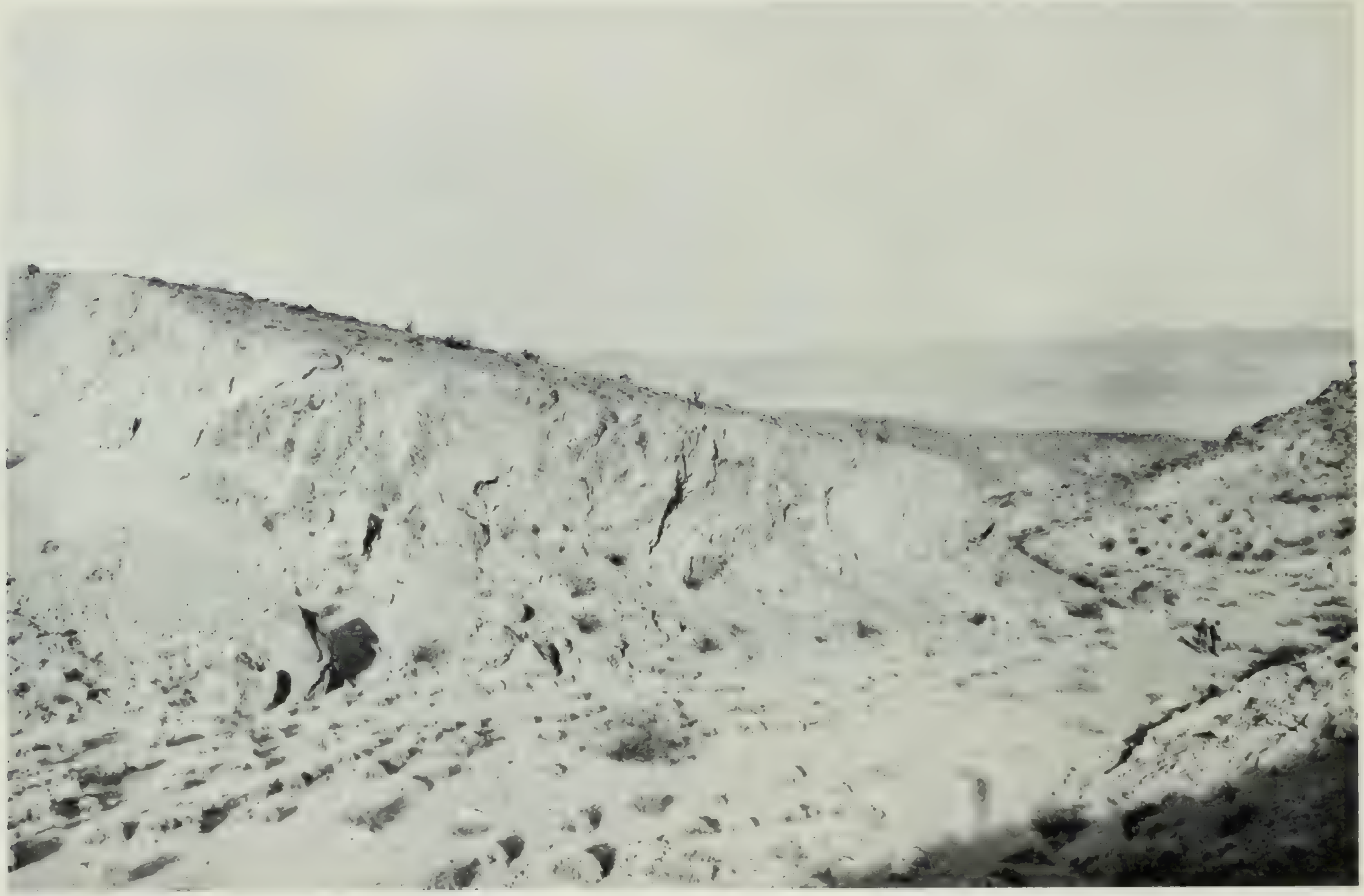

FIGURE 13. Large shattered mass of gneissic hornblende diorite, at least 150 feet in maximum dimension, that lies wholly within a section of Pliocene sedimentary strata near the south end of the Avawatz Mountains, San Bernardino County.

rocks (e.g., Fraser, 1931, pp. 506-508; Larsen, 1948, pp. 32-36), and some of them assuredly have undergone subsequent contact metamorphism. Some of the pre-Cambrian rocks may well have been metamorphosed three times or more. The present net effects of metamorphism in rocks of like age are known to vary considerably, and commonly abruptly, from one area to another, but much more information is needed to establish the regional trends in metamorphic intensity, as well as the nature and mechanism of material transfer during the different episodes of metamorphism.

Paleozoic and Mesozoic Sedimentation. The general distribution of sedimentary basins and facies during Paleozoic and Mesozoic time is becoming well known for the Great Basin region of Nevada and eastern California, and it seems increasingly likely that some of the trends can be projected southward and southwestward in southern California. Despite the spotty exposures of these older rocks in much of southern California, as well as their varying degrees of metamorphism, near-lack of diagnostic fossils, and large-scale displacements by faulting, the little work done thus far on sedimentary facies already has yielded encouraging results. Indeed, it may prove to be one of the best approaches to the dating of some of the rocks, and even to the ultimate evaluation of major fault movements in the region.

Age and Correlation of the Mesozoic Plutonic Rocks. Plutonic rocks of Mesozoic age can be traced almost continuously from the Baja California peninsula northward to the central Sierra Nevada, and in general they represent two huge composite batholiths. The southern California batholith, which underlies most of the Peninsular Range province, is thought to be early Upper Cretaceous in age, mainly on the basis of relations in northern Baja California between fossiliferous sedimentary rocks and several plutonic masses that are regarded as parts of the batholith (Böse and Wittich, 1913; Woodford and Harriss, 1938). In contrast, the Sierra Nevada batholith is thought to be of late Jurassic age on the basis of stratigraphic evidence (Knopf, 1929, p. 14; Hinds, 1934). Some plutonic rocks in the Mojave Desert region have been assigned a Jurassic age, whereas others are regarded as post-Middle Cretaceous (Hewett, Contribution 1, Chapter II). Age assignments for the Mesozoic plutonic rocks in the areas between the Peninsular Ranges and the Sierra Nevada appear to reflect the preferences of individual geologists for correlations with one major batholith or the other.

Geochemical determinations of age have yielded estimates that range from 100 million years (Larsen, et al., 1952) and 110 million years (Ahrens, 1949, p. 250) to as much as 147 million years (Davis and Aldrich, 1953, p. 380) for the southern California batholith; about 100 million years for the Sierra Nevada batholith (P. C. Bateman, personal communication); 150 and 155 million years for two pegmatite bodies associated with plutonic rocks in the Mojave Desert region (Hewett and Glass, 1953); and an average of about 100 million years for several plutonic masses in the Transverse Range province (G. J. Neuerburg, personal communication). These represent a range from Middle Jurassic to Middle Cretaceous. Most of the estimates are regarded as accurate to the nearest 10 percent, but the discrepancies among the results obtained from different methods suggest that further refinements are needed before determinations of absolute age can be used for the more exact correlations that are desired.

As Woodford (1939, p. 258) points out, "If the southern batholiths are really mid-Cretaceous, a puzzling problem arises . . . Where does the Cretaceous pluton end and the Jurassic . . . one begin? Is it possible that the Sierra Nevada pluton was also intruded in mid-Cretaceous time?" Further, if the stratigraphic evidence in Baja California can be accepted, the southern California batholith must have been emplaced, cooled to solidification in at least its upper portions (see Larsen, 1945), in part unroofed by erosion, and then covered by marine sediments—all during Upper Cretaceous time!

Deposition and Life in the Tertiary Basins. The rocks and faunas of the Tertiary basins of deposition, and especially those in the coastal region, probably have received more detailed attention than any other major element of southern California geology (see Chapters II, III, and IX of this volume). Only a part of what is known has been published, however, and only a few recent attempts have been made to summarize the results of work done to date (e.g., Woodford, et al., Contribution 5, Chapter II; Durham, Contribution 4, Chapter III). Exciting possibilities remain for further integration of data on tectonic environment, mechanics and chemistry of sedimentation and lithification, paleoecology, and basin-sediment deformation with the wealth of available surface and subsurface information on thickness, lithology, and faunal relationships.

The western part of the Transverse Range province appears to be a particularly inviting area for further study. Thick, well-exposed, and carefully studied sections provide an almost unique opportunity for correlation of environments and processes in three adjoining, and at times interconnected, basins of dominantly marine, lacustrine, and fluviatile deposition, respectively. Farther east and northeast, in the Mojave Desert region, are nonmarine basins of Cenozoic deposition in which the occurrence of salines and associated clastic deposits still raises important questions of genesis. Happily, many of these questions are being addressed at the present time as part of a vigorous program of investigations by the U. S. Geological Survey.

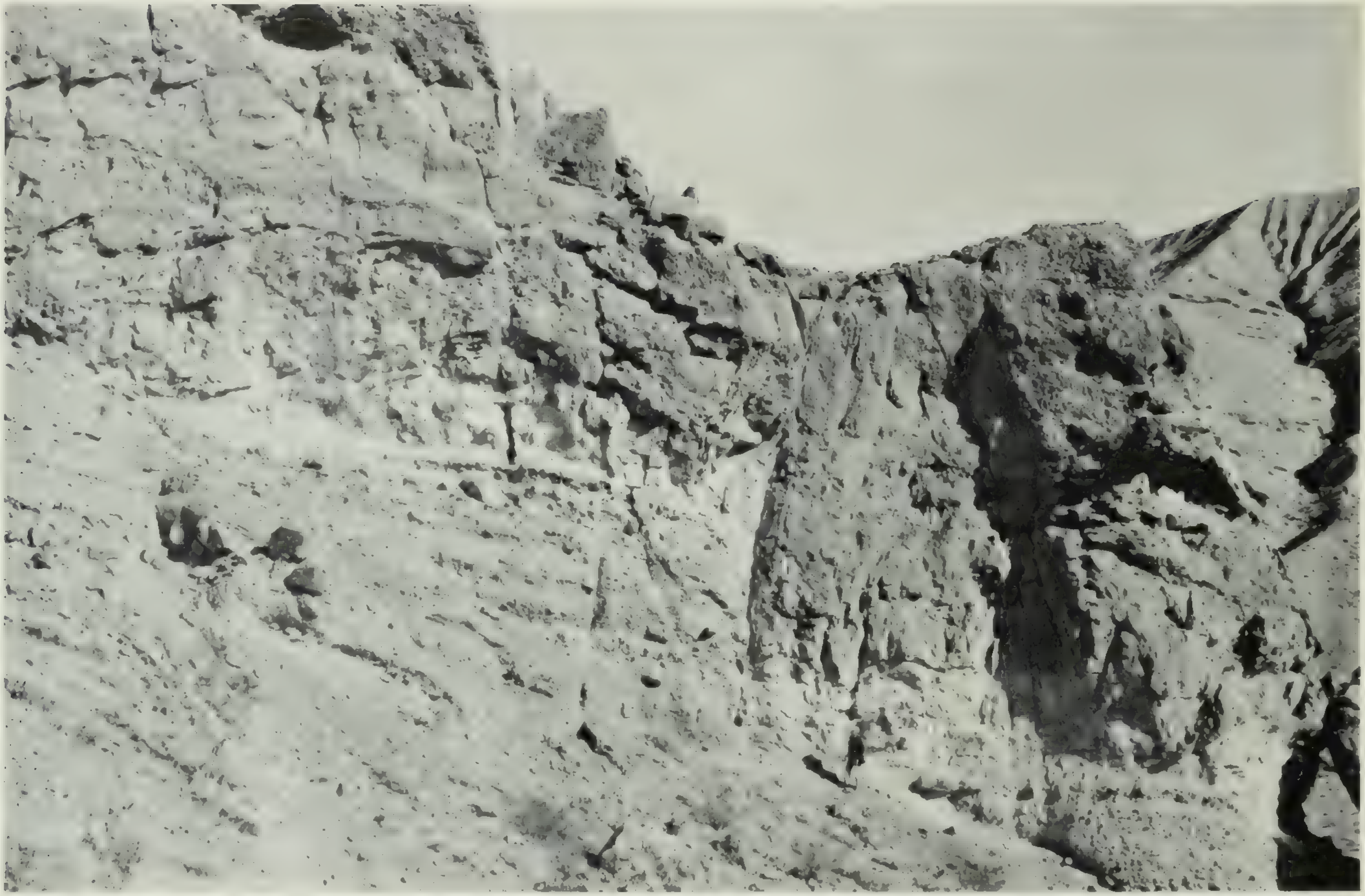

FIGURE 14. Massive layer of chaotic breccia, about 40 feet thick, within a section of Plio-Pleistocene alluvial-fan deposits in lower Emigrant Canyon, Panamint Range. The layer consists mainly of dolomite fragments about 2 inches in average diameter, and is underlain by a thin layer of bluish gray schist-bearing breccia.

Chaotic Breccias. Masses of breccia that are best described as chaotic are present in nearly all parts of southern California, and are especially abundant in the Basin-Range, Mojave Desert, Colorado Desert, and Transverse Range provinces. They appear within sections of Cenozoic nonmarine strata or rest directly upon older rocks, and their spatial relations to the associated rocks are not everywhere clear. Some of these breccias consist of rock fragments that commonly are less than a foot in diameter, but others are much coarser, and contain disordered masses of rock whose maximum dimensions are measured in tens and even hundreds of feet (fig. 13). Many of the breccias are essentially monolithologic, and others are lithologically heterogeneous.

A sedimentary origin is readily deduced for most of the breccia masses that are interlayered or intertongued with finer-grained strata (fig. 14), and they appear to have accumulated as mud flows and debris flows. The origin of others, including most of those that contain gigantic fragments of rock and have been termed ''chaos,'' is much less clear. These giant breccias are most abundant in the interior parts of the region, where they have been studied by Noble (1941), Hewett (1954), and many others. They have been variously interpreted as representing the disordered soles, tongues, or other parts of low-angle thrust faults, as deposits of composite thrust fault-sedimentary origin, or as deposits whose formation was associated with major high-angle faulting.

Whether wholly tectonic, wholly sedimentary, or of composite origin, most of these giant breccias seem to be related to large-scale faulting. Low-angle thrust faulting of very great net slip has been invoked to explain the occurrences of chaos in the southern Death Valley region (Noble, 1941; Curry, Contribution 7, Chapter IV), but recent work has shown that many of these breccia masses are of sedimentary origin and probably are more closely related to high-angle faulting (Noble and Wright, Contribution 10, Chapter II). Much further study is needed to define accurately the respective roles of faulting and sedimentation, and of extensional and compressional faulting, in the development of these remarkable rocks.

Surfaces of Erosion. Broad surfaces of erosion are present in all of southern California's natural provinces, and appear at many different levels. Most of them were formed during the Quaternary period, and a few others seem to represent older surfaces that have been exhumed from beneath a cover of sedimentary or volcanic rocks. Although some of the surfaces are known to have been developed at different times, there has been considerable argument as to whether those in certain regions are remnants of much more extensive surfaces that were segmented and displaced by block faulting. It seems clear that even the most careful measurements of areal and vertical distribution of recognizable surfaces can serve as little more than a start toward resolution of this question, which is a particularly troublesome one in areas that are underlain by massive crystalline rocks.

Marine terraces, some of which have been deformed, are well preserved in the coastal areas. Their correlation, not only with one another, but with fluviatile terraces and broader surfaces of erosion farther inland, as well as with features of the offshore area, constitutes a formidable problem (e.g., Putnam, 1942; Upson, 1951; Sharp, Contribution 1, Chapter V). Solution of this problem will figure vitally in the reconstruction of Pleistocene and Recent events in the region, just as correlation of certain erosion surfaces already has contributed to an understanding of the Quaternary and late Tertiary history of the Mojave Desert region (Hewett, Contribution 1, Chapter II).

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2. CLIMATE, VEGETATION, AND LAND USE IN SOUTHERN CALIFORNIA

By Harry P. Bailey *

CLIMATE

In an area of bold relief, like southern California, the landscape is dominated by craggy mountains, undulating hills, and sweeping plains. Vegetation, mantling the bare earth, supplies an array of textures and colors that adds to the scenic variety of the region. Climate is a less visible entity, and requires time for its full expression, but it is nonetheless a vital factor in the interpretation of the natural domain.

Landforms, vegetation, and climate comprise the major elements of the natural landscape. Of the three factors, climate is the best indicator of the state of the landscape as a whole. While it is true that climate is not a completely independent agent, and that the surface of the earth and plants growing upon it do appreciably modify the properties of the atmosphere, it also is true that these modifying influences are not as significant as the direct effects of climate on them. Thus, climate stands in many respects as a common denominator in the natural realm.

The climatic factor is strongly felt by man, who necessarily lives with, and contends with, his physical surroundings. Water supply, flood control, and air pollution are examples of the important climate-based problems that are faced by man in southern California.

Air Flow, Terrain, and Climate. In broadest generalization, the atmosphere over southern Cailfornia is mild in temperature and placid in movement. In consequence, the region is warm, sunny, and rather dry as compared with most parts of the United States.

This general statement does require three major qualifications. Although the summers are notably fair and calm, the winters have more variable weather, including periods of windiness, cloudiness, and precipitation. During much of the year, air moves from the nearby Pacific Ocean to the land. This change of environment modifies the lowest layers of the atmosphere, and results in differences among the climates of areas along the path of travel of air moving from the coastline toward the interior. Further, the pronounced relief of southern California brings some of its surface into contact with upper air whose properties are quite different from those of the atmosphere at sea level. Elevated terrain itself influences the movements of air passing over it, and so may either augment or diminish the precipitation process. Thus, the surface configuration of the region tends greatly to complicate the distribution of climates.

A fuller statement of the climate of southern California, then, would include the following features:

(A.) Nearly all of the annual precipitation occurs during the winter half-year.

(B.) Although temperatures generally are warm, they are modified according to the nearness of the sea and the effects of terrain. The difference between sea-surface and land-surface temperatures is greatest in summer, when interior valleys at low altitudes regularly experience maxima of more than 100° F. In contrast, cool marine air keeps afternoon temperatures between 70° and 90° along the coast. At intermediate points the temperatures are intermediate, depending in detail upon the freedom with which sea air can move over the terrain.

In winter, if day and night temperatures are considered together, coastal and interior areas of the same altitude show nearly the same average value—about 50° at sea level. This is possible because winter circulation is dominated by air flowing from land to sea, and this air has undergone most of its adjustment to the land surface by the time it reaches southern California. Elsewhere, however, the equality in distribution of winter temperatures is altered by the fact that most interior points are higher than those of the coastal zone, and so are colder. Thus the winter temperatures of coastal cities are similar to those only of low-lying interior areas, such as the Coachella and Imperial Valleys.

Precipitation is also affected by the factor of distance from the sea, probably in the sense of a slight decline inland, but this relation is completely obscured by the much greater effects of terrain.

(C.) The influences of terrain underlie many major and minor aspects of climatic distribution in southern California. They are best summarized by considering separately the summer and winter half-years.

Terrain affects the summer (April-September) climate of lowland areas chiefly by regulating the inblowing movement of the sea breeze. Where that shallow layer of marine air can move with ease, temperatures increase gradually inland; but if the marine air is blocked by hills or mountains, valleys only a few miles from the sea become 20° to 30° warmer than the coastline, and thermal conditions typical of points 50 miles or more from the coast are found close to the sea, providing one of the strongest temperature gradients to be found.

Coastal slopes of hills and mountains near the ocean lead not only to greater warmth inland, but upward in the atmosphere as well. Levels up to 5,000 feet are warmer in summer than the underlying marine air brought in by the sea breeze. This temperature inversion leads to confinement of smoke and dust close to the ground, and is a fundamental aspect of the smog problem in the Los Angeles area. Stratus clouds often are present in the marine air, too, and the coast thus is less sunny and is more subject to restrictions of visibility than the interior. Above 5,000 feet, air temperatures decrease in a more nearly normal manner, but, considering the altitude, all mountain areas of southern California are warm in summer.

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Summer precipitation is almost entirely lacking in the coastal lowlands that are strongly affected by the indraft of the sea breeze, and, although this precipitation is more frequent over the higher mountains and interior plains, it is not reckoned as a significant element in the climate of southern California. Lightning connected with thunder showers does start many forest fires, presenting a serious problem because the rain seldom follows in amounts sufficient to serve as an extinguisher.

In winter (October-March), as in summer, terrain modifies climate by blocking flows of air. However, the results in winter are much more dramatic, for it is then that the atmosphere is in a state where clouds and precipitation readily can form. This condition, related to occasional storm systems passing over southern California, brings unstable air from the sea toward the land. Slopes facing the sea are rainiest, and those facing inland are driest. Coastal basins thus are much better watered than those of the interior, and interior localities are sunnier and often more pleasant in winter than the damp and cloudy coast.

A flow of air onshore, although it is the source of rain and hence is of climatic significance, is not a prevailing condition in winter. More frequent is a movement of air coastward and downward from high ground in Nevada and Arizona. Such offshore flow brings dry weather to the southern California coast, and is known locally as "Santa Ana" weather. In the middle of winter this continental air is cool, and some of the imported air masses are cold enough to cause nighttime temperatures well below the freezing point. In spring and fall the Santa Ana air is warmer, and sometimes brings truly hot weather, a condition which, in combination with very low humidities, creates high fire hazard in many areas. A few times each winter the continental flow attains sufficient velocity to bring destructive winds to the coast, a condition usually prevented by the nearly continuous rampart of intervening mountains.

Altitude is an important control of temperature in winter, and decrease in temperature with increase in altitude is typical. This circumstance creates a much sharper contrast in the thermal conditions of lowlands and uplands than in summer. The plains of the Mojave Desert, standing at altitudes between 2,000 and 3,000 feet, frequently are swept by chill winds during the cooler months of the year, and the mountains of this region are cooler still, a midwinter snow cover being common at altitudes of 8,000 feet or more. As a traverse across southern California necessarily crosses high ground, a journey inland during the winter season involves decreasing temperatures as the coast is left behind, which is an experience opposite from that of summer travel. Hence, seasonal contrasts of temperature increase markedly away from the coast.

Climatic Types of Southern California. A map of climates, shown in figure 1, illustrates the relations described in the preceding section. Twelve climatic types appear on this map, and are grouped into four phases. Designation of the climatic types is based on the assumption that the range of climatic conditions in southern California could be adequately shown at the scale of the map by assigning four temperature classes and four moisture classes. Of the 16 possible combinations of temperature with moisture, 12 actually occur in southern California.

The temperature classes are based on categories of average annual temperature, as defined below.[*] Definitions of the moisture classes cannot be expressed by simple categories of average annual rainfall, as they embody the principle that the needs of plant life are met with equal effectiveness by less rainfall in cool climates (as judged by average annual temperature) and cool seasons (as judged by the percentage of the year's rain that falls in the winter half-year) than in hot climates and hot seasons. If it is understood that both temperature and moisture classes reflect chiefly the average annual conditions, the simple words used in the legend to the map, such

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[*] The definitions of all terms appearing on the climatic map are as follows:

Thermal classes:

Hot (T = 69 or more)
Warm (T = 58 to 68, incl.)
Cool (T = 44 to 57, incl.)
Cold (T = less than 44)

Where *T* is the average annual temperature in degrees Fahrenheit.

Moisture classes:

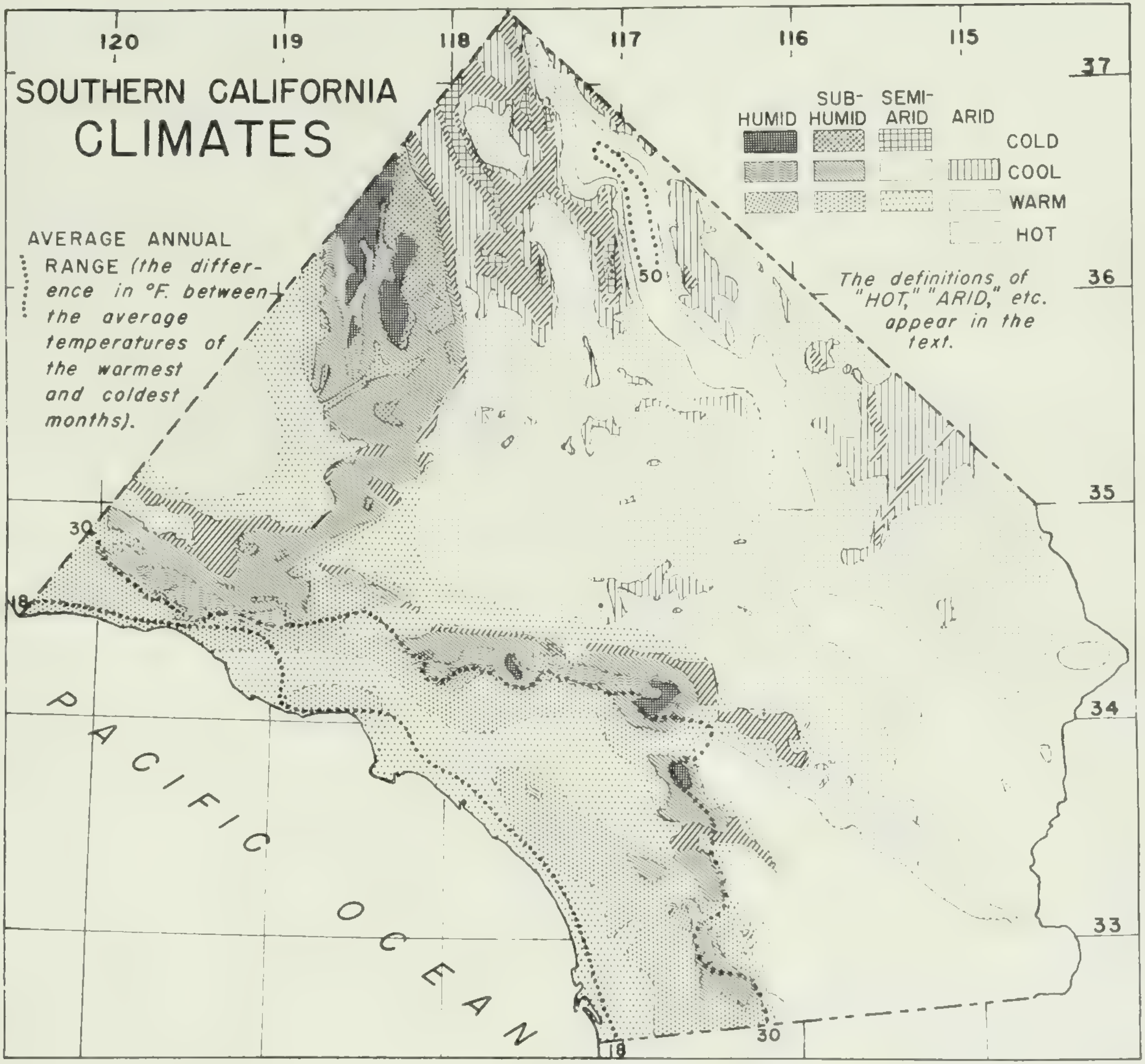
Humid (P = 0.76 (T — R/4), or more)
Subhumid (P = 0.41 (T — R/4) to P = 0.75 (T — R/4), incl.)
Semiarid (P = 0.22 (T — R/4) to P = 0.40 (T — R/4), incl.)
Arid (P is less than 0.22 (T — R/4))

Where *T* is the same as in the thermal classes,
P is the average annual precipitation, in inches, and
R is the percentage of the average annual precipitation that falls during the winter half-year (October-March, inclusive).

Climatic phases:

Maritime fringe (average annual range is less than 18°F.) Intermediate hills and valleys (average annual range is 18° to 29°, incl.)	Coastal province
Interior (average annual range is 30° to 49°, inclusive) Death Valley (average annual range is 50° or more)	Interior province

Where the *average annual range* is the difference in degrees Fahrenheit between the average temperatures of the warmest and coldest months.


SOUTHERN CALIFORNIA
CLIMATES
HUMID
SUB-HUMID
SEMI-ARID
ARID
COLD
COOL
WARM
HOT
AVERAGE ANNUAL RANGE (the difference in °F. between the average temperatures of the warmest and coldest months).
The definitions of "HOT," "ARID," etc. appear in the text.
120
119
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18
PACIFIC OCEAN

FIGURE 1.

Table 1. The number of stations in each climatic type agreeing with stipulated climatic characteristics of southern California.[1]

CLIMATIC TYPE	Number of stations[2]	Average annual precipitation (inches)					Average annual frequency of precipitation (days with more than .01 inches)				Average annual snowfall (inches)				Percentage of the average annual precipitation occurring in the winter half-year (October-March)				Average annual growing season (days)					No report
		0 9	10 19	20 29	30 39	40 49	0 19	20 39	40 59	No report	0 29	30 59	60 79	No report	60 69	70 79	80 89	90 99	150 199	200 249	250 299	300 349	350 365	
HOT-arid	12	+ √ +++++ +++++					+++++			+ √ +++++				+ √ +++++ +++++	+++++	√ +++++	+				++++	+ +++++		+ √
WARM-arid	7	++ +++++					++	+		++++				++ +++++	+	+++	+++			+++	++			++
semiarid	24		••++ ••••• ••••• oooo• ooooo					• oo•••	+ o••••	•+ o•••• ooooo				••++ ••••• ••••• oooo• ooooo		o•	+ ••••+ ••••• oo••• ooooo	o		••	•••+ •••••	o•••	oooo	oooo+
subhumid	15		•••• o••••	• •••••				••••	o•••	•• •••••	•			•••• ••••• o••••		••	•• ••••• o••••	•		••••	•••	o•	•	•••••
humid	1				•					•				•			•					•		
COOL-arid	3	+++						+++			+			++			+++		+++					
semiarid	1		+						+					+			+		+					
subhumid	7			•••	+ +++			+	••++	•+		•++	•++	•		••	•++++		•++					••++
humid	1					+				+				•			+		+					
COLD	0																							

CLIMATIC TYPE	Number of stations	Average January minima (°F.)				Average July maxima (°F.)						Lowest temperature of record (°F.)						Hottest temperature of record (°F.)				
		20 29	30 39	40 49	No report	70 79	80 89	90 99	110 109	110 119	No report	-19 -10	-9 0	0 9	10 19	20 29	30 39	90 99	100 109	110 119	120 129	130 139
HOT-arid	12		+++ √ +++++	+++					+ +++++ +++++	√				+	√ +++++	+++++				+++	++ +++++	+ √
WARM-arid	7	++	++++		+			++	++++		+				++ +++++				+	+ +++++		
semiarid	24		+ ••••+ •••••	••• oooo• ooooo		oo ooooo	••• oo•••	••+ •••••	+					•	++ •••••	•••• oo••• ooooo	oo	ooo	+ ooooo	••••• ••••• o••••		
subhumid	15		•••• •••••	o••••	•	o	••	• ••••• •••••			•				•• •••••	••• o••••			•••••	••••• o••••		
humid	1			•				•							•					•		
COOL-arid	3	+++						+++				+	+	+					+++			
semiarid	1	+					+						+						+			
subhumid	7	••+++	+	•		•	+ ••+++						•++	•+	•+			••+	•+++			
humid	1		+				+							+					+			
COLD	0																					

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[1] All climatic data are from *U. S. Weather Bureau, 1930, Climatic summary of the United States, section 18—southern California and Owens Valley*, 41 pp., and *section 17—central California*, 64 pp.

[2] The climatic phases of the stations (see footnote, p. 32) are identified by symbols as follows:

- o Maritime fringe
- • Intermediate hills and valleys
- + Interior
- √ Death Valley

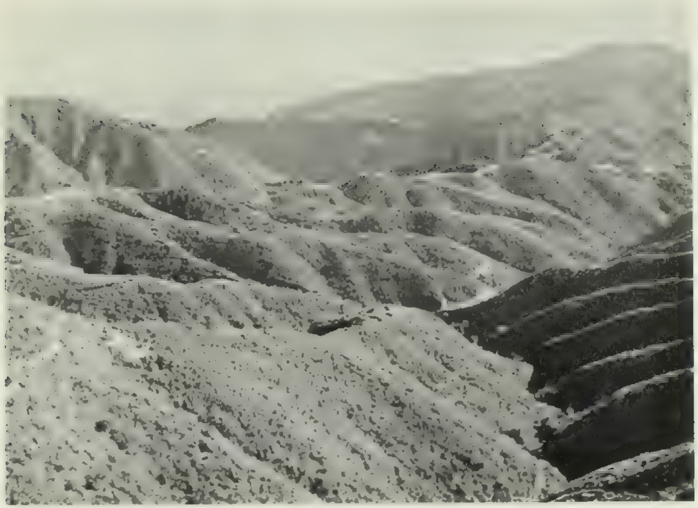


FIGURE 2. Chaparral, as it appears in the San Dimas Experimental Forest, at an altitude of about 2,500 feet on the south-facing slopes of the San Gabriel Mountains.

as hot, arid, and humid, become just as meaningful as the equations to which they refer.

The dotted lines on the map cross through the climatic types, and establish independent climatic phases. They are based on the average annual range of temperature (the difference between the average temperatures of the hottest and coldest months of the year), and also are defined in the footnote, page 32.

An examination of the pattern of climatic types shown in figure 1 will indicate a high degree of correspondence with the explanations given in the preceding section on air flow, climate, and terrain. The characterization of southern California as predominantly warm is shown by the large area covered by warm and hot thermal classes. The dryness of the region is revealed by the large area affected by arid or semiarid moisture classes. The effect of terrain in modifying the climate is shown clearly by the complexity of the climatic pattern in mountainous regions, and by the cooler and moister climatic types associated with them.

The change of climate from coast to interior is indicated partly by the greater aridity of the interior, and also by the increase in average annual range of temperature away from the sea. Particular attention should be given to the line of 30° average annual range, because it marks the division between the coastal and interior climates, as those terms are used in this study. It falls close to the first major topographic crest of the coastal mountains, as this crest would be approached from the sea.

As an aid in understanding the climatic characteristics of the regions, as illustrated in figure 1, table 1 shows selected categories of certain climatic elements. The number of stations in each region that agree with a stipulated climatic condition is shown in the body of the table. In the warm-semiarid climatic type, for example, in which summaries are available for 24 stations, seven report average maxima in July between 70° and 79° F., eight in the range 80° to 89°, eight in the range 90° to 99°, and one in the range 100° to 109°. This information is amplified by the use of symbols identifying the climatic phase to which each station belongs, and thus in the example just given it also can be determined that all seven stations in the 70° to 79° category are in the maritime fringe, and that the station reporting 100° to 109° is located in the interior.

A glance at table 1 shows why a detailed climatic map cannot be made solely on the basis of data from climatic stations. The cold thermal class fails to be represented by even a single station, as in southern California the requisite temperatures are found only on ground too high and rugged for habitation. In lieu of data from a conventional instrument shelter, records from radiosondes were consulted for those levels above habitation, and contours were freely used to supply details between stations, whether surface or free air.

One salient characteristic of southern California climate, the winter concentration of rainfall, is missing from the map. This factor has been deleted because all points in the region with moderate to heavy rainfall (subhumid or humid in moisture classification) receive a high percentage of the year's total during the winter half-year. Summer rain more nearly equals winter rain in the interior regions, but so little occurs there during either season that the matter of seasonal concentration loses significance. An approximate notion of the distribution of the degree of concentration of rainfall during the winter half-year can be gained from an inspection of table 1.

The following list of characteristics can serve as guides to the kinds of interpretation that are possible from the climatic map and the statistical table:

> The most nearly frost-free stations are located in the maritime fringe.
>
> The frequency of precipitation in southern California is surprisingly low, and no station reports an average annual figure of more than 59 days.
>
> By ordinary standards, only the coastal stations can be said to have a thermal regime in which temperatures are consistently within the zone of comfort. Hence, the "southern California climate" boasted of by many residents is a rather selective

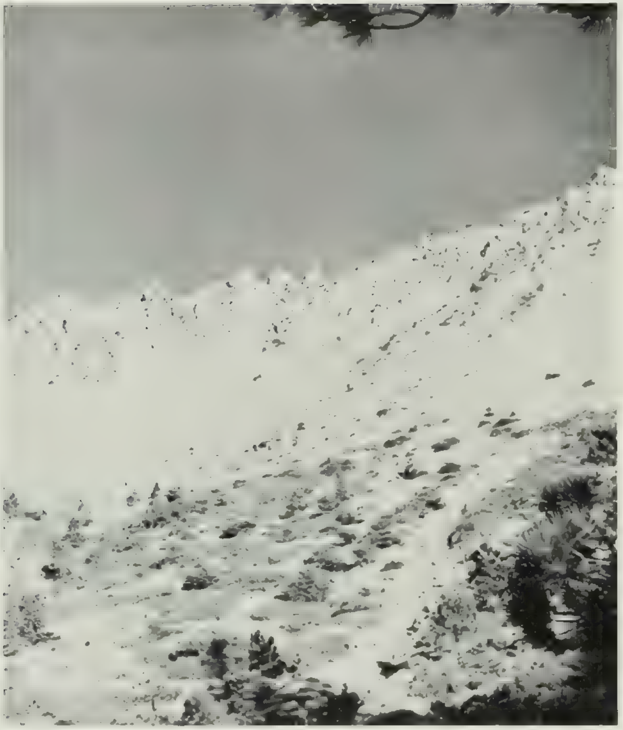


FIGURE 3. Subalpine flora at altitudes of 8,500 to 9,000 feet on the south face of San Antonio Peak, San Gabriel Mountains.

term, and actually applies mainly to warm-semiarid and warm-subhumid types within the coastal province.

Snow rarely falls in the hot and warm thermal areas. In contrast, it frequently falls in the cool regions, although it seldom lies long on the ground. In the cold regions, which are found only in the interior, most of the precipitation is in the form of snow, which is stored for weeks or months on the ground before melting.

Snow storage is only a slight factor in the stream regimes of southern California, as only a few scattered peaks are high enough to experience a cold climate. However, the Sierra Nevada does develop extensive snow fields, and large areas of cold climate are found even toward the southern end of the range. The isolated ranges inland from the Sierra Nevada and the coastal ranges appear to be relatively arid, and the chief effect of altitude is to modify temperature rather than rainfall. Nevertheless, points high enough to be ranked as cold seem never to be arid, and thus in southern California, at least, a cold-arid combination is not found.

Most of the densely populated and intensively farmed areas of southern California are located in semiarid or arid regions. Even the subhumid margins of the coastal ranges are too dry to sustain the level of development now characteristic of the upper San Gabriel and Santa Ana Valleys, where deficiency of water is made good only by inflow from nearby upland areas of greater moisture, and by import from distant drainage basins.

The diversity of climate in southern California is truly remarkable, especially when compared to the transitions that are typical in areas of subdued relief. For example, on the basis of average annual temperatures, southern California shows a thermal range equivalent to that found between the Gulf of Mexico and the Great Lakes. Similar comparisons could be made to indicate the magnitude of the range in moisture conditions, and in the average annual range of temperature.

PLANT COMMUNITIES

The vegetation of a region is the visible expression of the nature of its physical environment. Many of the differences in the plant cover in southern California are related to climatic influences, and the range of plant communities can be related to the distribution of the climatic types shown in figure 1.

The plant communities recognized here have been adapted from those outlined recently by Munz and Keck (1949), who carried out their work on a scale of generalization comparable to that employed here in defining climatic types. Of the 28 plant communities that are described by these investigators for California as a whole, 17 occur in southern California. Their description, climatic associations, and characteristic species appear in table 2.

Although practical considerations have been kept in mind in setting forth the plant communities, a good deal of inequity cannot be avoided in the factors of complexity and area covered. Coastal strand vegetation, for example, is areally insignificant as compared with most of the other plant communities, but it deserves recognition on the basis of a distinctive appearance and floral content. Chaparral represents the opposite extreme, as it covers a large area, is floristically complex, and is adapted to such a wide range of environments that it occurs in appreciable degree in areas of no less than seven climatic types. Nevertheless, for both types of vegetation the same rule has been followed in identification of the unit: each is a "regional element of the vegetation that is characterized by the presence of certain dominant species."

Plant Communities of the Coast. The coastal province of southern California, as defined climatically, lacks true forest, and even woodland is a minor element in its vegetal cover. Southern oak woodland (table 2) is found, to be sure, but it is restricted to shaded north-facing slopes, moist foothill sites, and valleys of rolling uplands. This community appears to be relictual, and it suffered noticeably during the drought of the 40's by the general decline of coast live-oak, its dominant member. Stream bottoms also are common sites of tree growth. Sycamores extend well away from the mountains along many stream banks, whereas alders, maples, and bays are mostly canyon dwellers. This stream-bottom woodland cuts across other plant communities as numerous ribbons along well-watered hill and mountain slopes, but it is not a sufficiently constant ecological type to deserve recognition as a major plant community, and so is not included in table 2.

Shrub vegetation, rather than trees, covers most of southern California. Coastal lowlands are dominated by the coastal sage community, which, at the height of its growth in spring, forms a grayish-green mantle through which little bare ground can be seen. During the long, dry California summer the formation thins somewhat, darkens, and in a distant view gives a salt-and-pepper aspect to the ground. Coastal sage forms a shrub cover, of medium density, that does not greatly impede walking.

Scattered throughout the region dominated by coastal sage are areas of grassland that are of obscure origin. Although native perennials are present, they are outnumbered by weedy annuals, imported from Europe, that are the product of past and present pastures. Coastal sage also is terminated along the coast by sand dunes, and by some tidal flats at stream mouths. The flats are identified by coastal strand and coastal salt marsh communities. Back of the coast, marshes are developed in some river beds of low gradient, and show a freshwater marsh vegetation. However, the best example of freshwater marsh vegetation in southern California is the Tulare lake bed, a major feature of the interior region.

The inner limit of coastal sage is its contact with chaparral, which generally lies on hill or mountain slopes well above the termination of the alluvial slopes of the lowlands. The line of contact is near the 1,000-foot contour in the Los Angeles region, but rises to about 4,000 feet in San Diego County. This distribution leaves most of the coastal sage community in the warm-semiarid climatic type, and places the lower margin of chaparral mainly in a warm-subhumid environment. Very little coastal sage crosses to areas of interior climate, but chaparral is not so circumscribed.

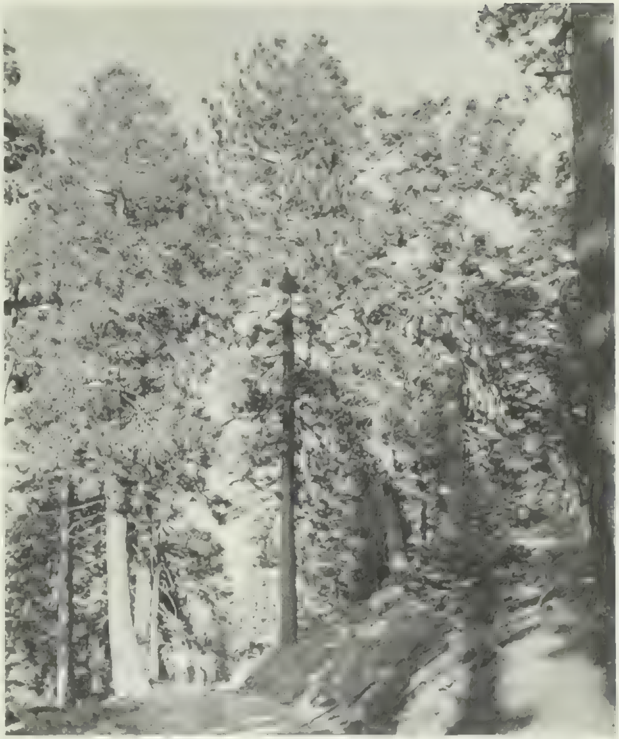


FIGURE 4. Pine-fir forest at an altitude of 8,000 feet in the Black Mountain section of the San Jacinto Mountains.

Chaparral, in its lower reaches, forms a cover of considerable density (fig. 2). Chamise (*Adenostama fasciculatum*) is clearly dominant in this zone, and contributes as much as 90 percent of all individuals. As its leaves are small, and the habit of the plant is quite spindly, chaparral dominated by chamise does not appear greatly different from the coastal sage with which it merges. Dominant at higher altitudes are various species of ceanothus and manzanita, plants with broad, thick leaves, mostly evergreen, and with stems of great strength. It is this phase of chaparral that justifies its characterization as an "elfin forest," and which gives the community a reputation for formidable resistance to penetration on

Table 2. Plant communities of southern California.[1]

Plant community	Physiognomy	Leading species	Associated climatic types[2]	
			Coastal	Interior
Coastal strand	Low or prostrate, commonly succulent	*Franseria bipinnatifida, Lupinus arboreus, Atriplex leucophylla, Mesembryanthemum nodiflorum, Convolvulus soldanella*	Warm-semiarid, warm-subhumid	
Coastal salt marsh	Low herbs or shrubs, commonly succulent	*Suaeda californica, Distichlis spicata, Frankenia grandifolia*	Warm-semiarid, warm-subhumid	
Freshwater marsh	Tall rushes in lowlands, grass-like in mountains	*Scirpus californicus, S. Olneyi, Typha domingensis,* (*T. angustifolia*)[2], *Carex senta*	Variable	
Coastal sage scrub	Plants half-shrubs, 1 to 5 feet tall, or somewhat woodier and larger	*Artemisia californica, Salvia apiana, S. leucophylla, Eriogonum fasciculatum, Encelia californica*	Warm-semiarid, (warm-subhumid)	
Valley grassland	Open grassland, with many flowering annuals in spring	Originally bunch grasses such as *Stipa pulchra, Poa scabrella, Aristida divaricata*	Warm-semiarid	Warm-arid, warm-semiarid
Southern oak woodland	Trees 20 to 60 feet tall, with grassland beneath	*Quercus agrifolia, Q. Engelmannii, Juglans californica*	Warm-subhumid, (warm-humid)	
Chaparral	Shrub vegetation, 3 to 10 feet high, commonly very dense, with broad thick leaves; evergreen	*Adenostama fasciculatum, Quercus dumosa, Ceanothus* species, *Arctostaphylos* species, *Cercocarpus betuloides*	Warm-subhumid cool-subhumid, (warm-semiarid, cool-humid)	Warm-subhumid, cool-subhumid, (cool-humid)
Foothill woodland	Trees 15 to 70 feet tall, dense or open, with scattered brush and grassland; oak parkland and digger pine	*Pinus sabiniana, P. Coulteri* in upper parts, *Quercus wilizenii, Q. lobata, Aesculus californica, Ribes quercetorum*		Warm-subhumid, cool-subhumid
Pine forest	Trees 75 to 200 feet tall, in extensive, continuous forests	*Pinus ponderosa, P. lambertiana, Libocedrus decurrens, Abies concolor, Quercus kelloggii*	(Cool-subhumid, cool-humid)	Cool-subhumid, cool-humid
Fir forest	Trees 100 feet tall or more, in dense forests	*Abies concolor, Pinus murrayana, P. monticola, P. jeffreyi, Castanopsis sempervirens*		Cold-subhumid, cold-humid
Alpine fell-fields	Almost entirely perennial herbs, scattered	*Festuca ovina, Oxyria digyna, Podistera nevadensis*		Cold-subhumid, cold-humid
Pinyon-juniper woodland	Trees 10 to 30 feet tall, in open stands with shrubs between	*Pinus monophylla, Juniperus californica* or *J. osteosperma* (*J. utahensis*), *Quercus dumosa* var. *turbinella, Purshia glandulosa, Cercocarpus ledifolius*		Cool-semiarid, cool-subhumid
Sagebrush scrub	Low, silvery gray shrubs 2 to 7 feet tall, interspersed with greener plants	*Artemisia tridentata, Coleogyne ramosissima, Chrysothamnus nauseosus,* sp. *speciusus,* and *mohavensis, Atriplex confertifolia*		Cool-semiarid, (cool-arid)
Shadscale scrub	Plants mainly 1 to 1.5 feet tall, shallow-rooted	*Atriplex confertifolia, Grayia spinosa, Eurotia lanata, Kochia californica, Guitierrezia sarothrae, Coleogyne ramosissima*		Cool-arid
Joshua tree woodland	Trees 10 to 30 feet high, scattered, with shrubs and herbs between	*Yucca brevifolia* and var. *Jaegeriana, Juniperus californica* or *J. osteosperma* (*J. utahensis*), *Salazaria mexicana, Lycium andersonii, Tetradymia spinosa*		Warm-arid, (cool-semiarid)
Creosote bush scrub	Shrubs 2 to 10 feet tall, widely spaced	*Larrea divaricata, Franseria dumosa, Hymenoclea salsola, Encelia farinosa, Echinocereus engelmannii, Opuntia Bigelovii, O. echinocarpa, Prosopis juliflora* var. *glandulosa*		Hot-arid, warm-arid, (warm-semiarid)
Alkali sink	Low scattered gray or fleshy halophytes	*Atriplex polycarpa, A. lentiformis, Allenrolfea occidentalis, Salicornica virginica, Frankenia grandifolia* var. *campestris*		Hot-arid, warm-arid, (cool-arid)

[1] Adapted from lists by Philip A. Munz and David D. Keck, 1949, *California Plant Communities,* El Aliso 2, pp. 87-105, 199-202.

[2] Parentheses indicate that the area occupied by the plant community is of small magnitude.

foot. Best seen in areas with climates close to the boundry between the warm-subhumid and cool-subhumid types, this dense stand of chaparral thoroughly mantles the slopes to which it is attached, and imparts to them a velvety texture, a dark green color, and almost complete protection from direct sunlight and unchecked rainfall.

Within areas whose climates are in the cool thermal class, temperatures decrease to the point where coniferous forest supplants chaparral, but it is not until the climate becomes classed as cold that chaparral is excluded. Chaparral also extends beyond the limits of the coastal climate, but its range does not include areas with the strong continental characteristics of the Great Basin, and so chaparral is absent in desert exposures.

Plant Communities of the Interior. The plant communities of the interior of southern California, like those of the coast, are chiefly shrub-form. In comparison with those of the coastal province, the shrub communities of the interior lowlands are scrubby, sparse in foliage, and widely spaced. Bare ground generally can be seen between the plants, and considerable tracts are essentially barren. It is also true, however, that major mountains lie within the province of the interior climates, so that the best forested regions of southern California also are developed there. The transition between montane forest and the shrubs of desert plains is made through desert woodland of considerable complexity.

The boundary between the interior climatic zone and the coastal zone lies mainly along the undulating crest of the coastal ranges. At altitudes below 3,000 to 4,000 feet, where the climate is classed as warm, chaparral extends freely into the interior province, but is gradually supplanted by desert woodland as rainfall lessens and the thermal environment becomes more extreme. At higher altitudes, where temperatures descend to the cool class, a transition also takes place between the coastal and interior phases. For this reason, the cool-subhumid and cool-humid climates of the coastal ranges lie mainly within the interior province, and it is in areas with these climatic types that coniferous forest appears. Above 10,000 feet coniferous forest is excluded by the effects of cold and wind, which allow only sparse, low-growing plants of the alpine fell-fields community (fig. 3). High-altitude vegetation is only locally developed on a few peaks of the coastal ranges (San Antonio, San Gorgonio, and San Jacinto), but is widespread along the crest of the Sierra Nevada.

Coniferous forest in southern California consists of two major plant communities, pine and fir (fig. 4). At 5,000 to 6,000 feet yellow pine (*Pinus ponderosa*) or its variant, jeffrey pine, generally displaces chaparral. Bigcone spruce commonly descends to lower altitudes, but rarely in groves of large size. Variety in the yellow pine zone is added by incense cedar, black oak, and coulter pine. White fir and sugar pine appear at higher altitudes, and at about 8,000 feet the fir community is established. Red fir (*Abies magnifica*) is absent from the coastal mountains, but white fir appears in excellent stands, along with lodgepole pine and aspen. Most of the fir community is in areas of cold climate.

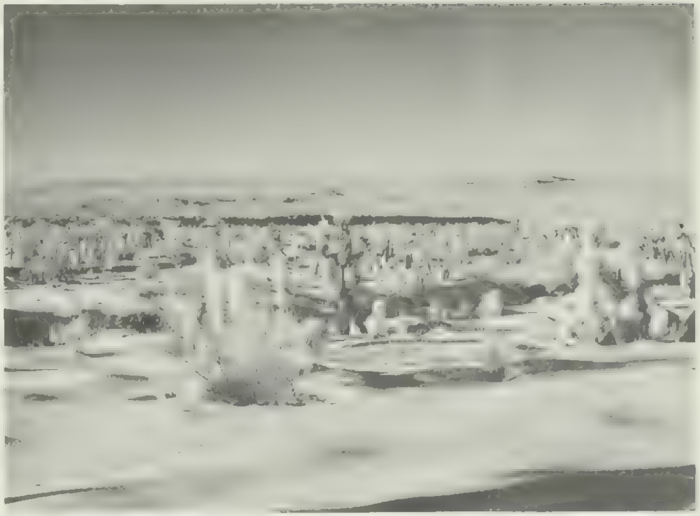
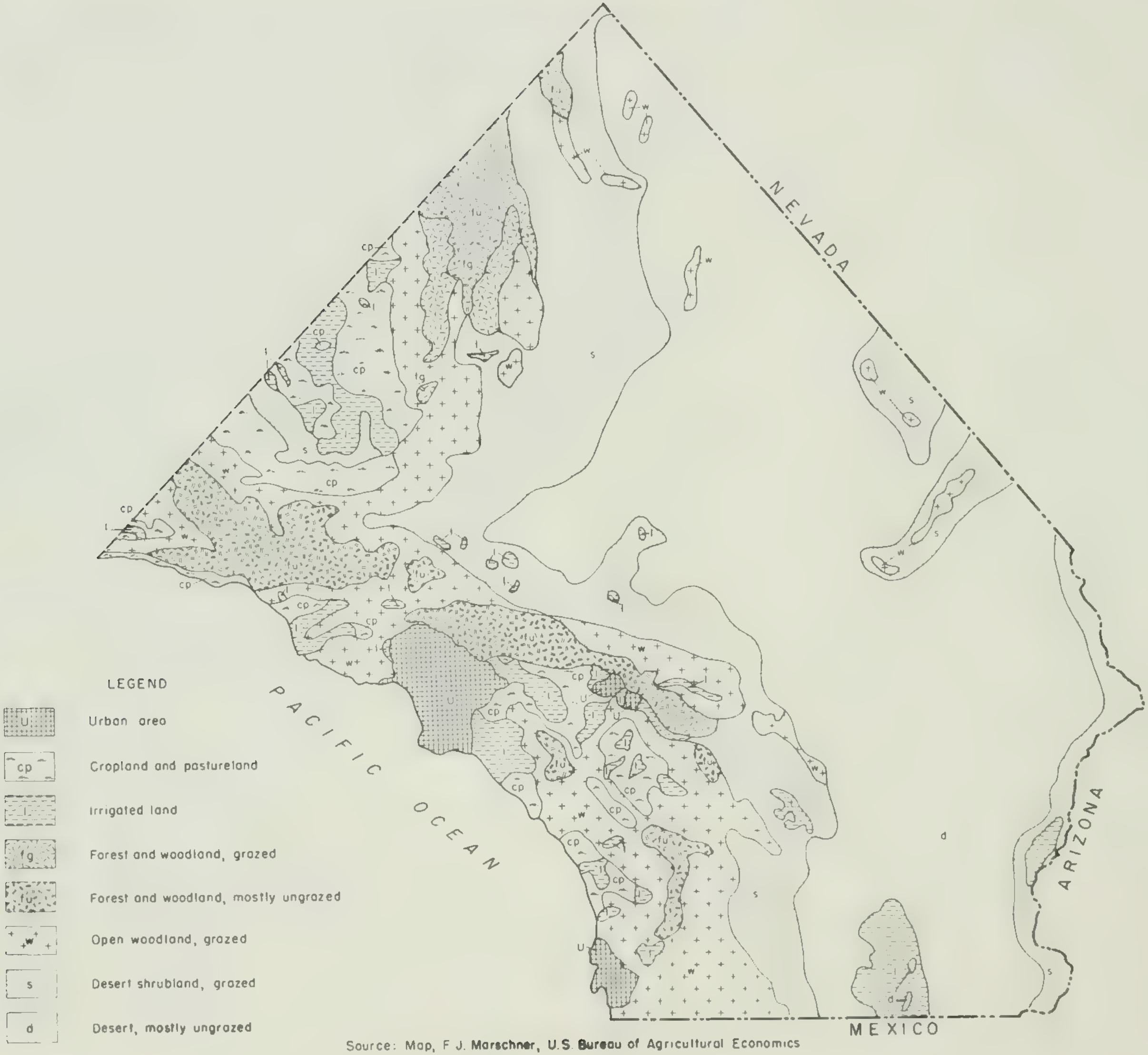


FIGURE 5. Joshua tree woodland under winter snow, at an altitude of 4,300 feet on the northern flank of the San Gabriel Mountains.

Somewhat similar transitions are seen in the Sierra Nevada, where the west face of the range receives abundant precipitation at high altitudes. The base of the range is much drier in the Tulare Basin than are the coastal lowlands, and so the foothills of the southern Sierra carry but a scant grass cover, in contrast to the relatively lush coastal sage community of the coastal ranges. With increase of altitude in the Sierra Nevada, liveoak appears in valleys, and digger pine is present on surrounding slopes (the Foothill Woodland of Munz and Keck), along with scattered shrubs. The whole is underlain by a grassy understory, but at 4,000 to 5,000 feet chaparral becomes dominant. The higher zones are much like those described for the coastal mountains, the chief differences appearing in the subalpine and alpine zones.

Descent from the crest of the coastal ranges and Sierra Nevada toward the Great Basin brings about a transition to plant communi-


NEVADA
ARIZONA
MEXICO
PACIFIC OCEAN
LEGEND
U Urban area
cp Cropland and pastureland
I Irrigated land
fg Forest and woodland, grazed
fu Forest and woodland, mostly ungrazed
w Open woodland, grazed
s Desert shrubland, grazed
d Desert, mostly ungrazed

Source: Map, F. J. Marschner, U. S. Bureau of Agricultural Economics

FIGURE 6. Major land uses in southern California.

ties that are adapted to warmer and drier environments. The transition is most rapid along the bold eastern face of the Sierra Nevada, where precipitation decreases sharply beyond the crest. The mountains bordering the Great Basin farther south allow more gradual changes in temperature and precipitation, and hence the plant communities there take on different characteristics.

Along the Sierra Nevada the coniferous forest descends to about 8,000 feet, where a narrow zone of pinyon-juniper woodland commences. That community, in turn, gives way to sagebrush at 5,000 to 6,000 feet, at the upper margin of the cool-arid climate. In the Transverse Ranges, in contrast, the coniferous forest reaches somewhat lower altitudes, and the zone of pinyon-juniper woodland is much broader, as semiarid conditions are maintained throughout the range of cool climates. On the high floor of the western Mojave Desert, a warm-semiarid climate extends for several miles beyond the mountains, creating an apron in which the Joshua tree woodland extends along a broad front at the northern flank of the Transverse Ranges (fig. 5). Farther east and south, where the mountains descend to the low floor of the Coachella-Imperial Valley, aridity is once again established at a zone well above the valley floor.

It is on the extensive desert plains of southeastern California that the shrub communities of the interior are found. Where soils are coarse and drainage is good, the creosote bush community dominates in areas with warm-arid and hot-arid climates, which prevail throughout the Mojave and Sonoran desert regions. The central parts of basins commonly are filled with fine-grained detritus through which water drains slowly, and which is affected more or less by saline accumulations. These factors bring into dominance the alkali sink community.

Over vast areas of the interior, creosote bush (*Larrea divaricata*) and burro-weed (*Franseria dumosa*) are almost the only conspicuous plants in view. Stunted and widely spaced, they somehow survive in a region that commonly furnishes them no rain for a year at a time. At the lowest and hottest sites, creosote bush attains a height of only 2 or 3 feet, but as altitude increases and the climate becomes more nearly semiarid, as it does toward the boundary of the Mojave Desert against the Transverse Ranges, this bush increases in luxuriance and reaches heights of as much as 10 feet. Under these more genial circumstances other plants are added to the cover, and the density of the assemblage is intimately related to the terrain, even minor water courses showing a denser spacing than dry interfluves. This enrichment of the desert flora can be seen along U. S. Highway 66 between Victorville and the crest of Cajon Pass, where the transition from creosote bush to Joshua tree woodland occurs.

In the areas east of the coastal ranges and the Sierra Nevada, increases in altitude result in only slight increases of rainfall. Thus, the isolated mountains of the Basin-Range province are not as humid in aspect as the coastal ranges or the western face of the Sierra Nevada. Areas high enough to be classed as cool (above 4,000 feet) are nonetheless mainly arid. Where the aridity is extreme, as in Owens Valley, the shadscale community is found; the presence of the sagebrush assemblage (dominated by *Artemisia tridentata*) is indicative of greater moisture. The higher parts of the cool thermal region become semiarid, which allows the pinyon-juniper woodland to be established. Only a few desert mountains of southern California are high enough to reach the cold-semiarid condition, and the vegetational changes associated with it affect areas too small to be noted here.

Conclusions. It is clear that shrub vegetation, in its several community forms, is the dominant type of vegetation in southern California. Desert shrubs are found over an area greater than the combined areas of all other communities, but it is not to be inferred that desert plants contribute the greatest amount of woody material. If southern California's mantle of vegetation could be weighed, its center of gravity doubtless would lie well toward the coastal province, where the assemblages are dense and the individuals accumulate considerable wood.

In examining the areal relations between climatic types and plant communities, it can be seen that a perfect correspondence is lacking, but that many approximations are apparent. For example, it is noteworthy that the warm climates, regardless of moisture class, fail to develop a forest cover. The forest communities lie exclusively within areas of the cool and cold thermal classes. It is also true, however, that trees are lacking, whether as woodland or forest, where the climate is arid, and that they are scarce under semiarid conditions. Most of the trees occur with subhumid and humid moisture, and cool or cold thermal conditions.

Seasonal contrasts in temperature also are important. Southern oak woodland appears in the coastal province mainly in warm-subhumid sites, but the same climatic type in the interior, as seen in the foothills of the Sierra Nevada, gives rise to foothill woodland that is silimar in character, but different floristically. Coastal sage, too, appears to be limited in its distribution by the factor of extreme temperature range.

That soil conditions also are important in controlling the areal distribution of vegetation cannot be denied. Coastal strand, marshland, and alkali sink communities are excellent examples, but even in these places climate exercises a secondary effect, particularly in the coastal strand assemblage where the vegetation changes progressively as the coast is followed from south to north.

By and large, the striking diversity of climate in southern California is fully demonstrated by the flora of the region. One can see, framed between the lofty trunks of a yellow pine forest, virtually barren playas, and rocky hills nearly as bare, that are not more than 20 miles distant. And within the intermediate zone is a host of gradations between plants and their environment.

LAND USE

The large movement of population to California during the past half-century and the surging economic tempo of the Nation have combined to create many dynamic forces leading to rapid change in the appearance of the southern California region. Out of the complex reaction between cultural and natural factors has arisen the present landscape of the region, marked by considerable diversity and many sudden transitions.

The major land uses in southern California are shown in figure 6. Congregated in the coastal lowlands are the major urban areas and much of the irrigated land. Irrigated land also appears in the Coachella-Imperial Valley and in lesser areas adjacent to the Colorado River. Farther to the north, and lying mainly beyond the scope of this study, is the Great Valley of California, which contains most of the irrigated parts of the State.

The less intense land uses implied by areas of unirrigated cropland and various forms of grazing are widely distributed over the hilly and desert sections of southern California. In their contacts with irrigated lowlands, they supply a very striking contrast between closely tilled fields and verdant orchards, on one hand, and the natural vegetation of grazing and brush lands, on the other. Extensive forms of land use occupy most of the area of the map, and dominate the view of the region when it is approached by air from the north or east.

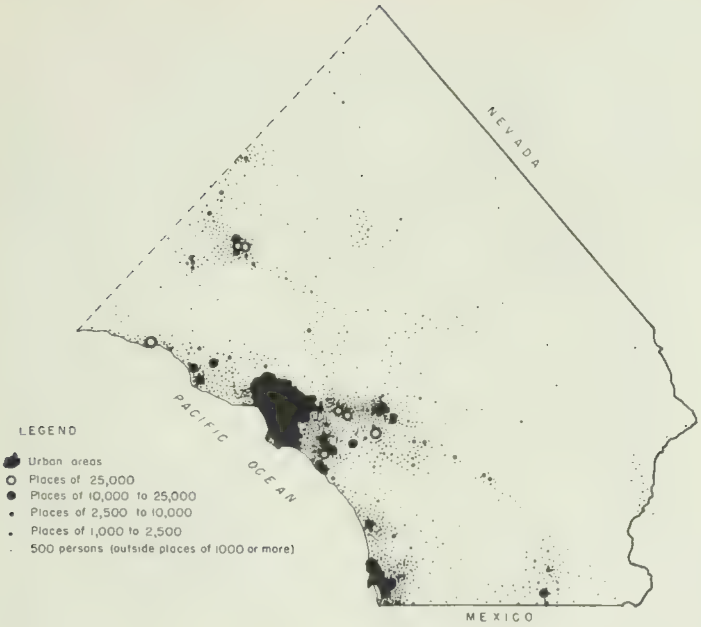
Despite the large areas of unfavorable terrain and climate, the agricultural productivity of southern California is very high. With the single exception of Inyo County, all of the counties that are wholly or mainly within the confines of the area of figure 6 are ranked among the 31 most productive counties of the Nation. According to the census of 1950, Los Angeles County ranked first, as it had in the previous census, and Kern County ranked third. No single crop, or allied group of crops, accounts for this high standing of southern California counties. Los Angeles, San Bernardino, San Diego, and Santa Barbara Counties derive their chief sources of agricultural income from the sale of dairy products to local outlets. Orange, Riverside, and Ventura Counties produce mainly fruits and nuts, Imperial County receives the greatest return from vegetables, and Kern County from field crops such as cotton and potatoes. All of these commodities enter national markets as well as local ones. Inyo County, in a cooler climate and without the advantage of abundant water for irrigation, supports a relatively extensive form of livestock production.

The variety in crop production is related in part to the topographic and climatic diversity of the region. To an important degree, however, the possibility of irrigation determines the agricultural practices. In the coastal section, where the climate is semiarid or subhumid (fig. 1), dry farming is possible; these "Mediterranean" climates are traditionally connected with the cultivation of wheat and other grains. Inland, where the moisture deficiency is greater, the returns from dry farming are uncertain. Irrigation supplements the natural water supply of the coastal basins, and allows dependable production of high-value crops, such as citrus. In the interior, irrigation must supply nearly all of the water needed, and both the acreage under irrigation and the amount of water used are very large. Both Imperial and Kern Counties report more than twice as many irrigated acres as any coastal county, Kern having reached nearly half a million acres in 1950.

Farmland, even when irrigated, cannot compete in value with city property, and thus in Los Angeles County, where urban growth is greatest, the acreage of harvested cropland is steadily decreasing. This also is shown by downward trends in production of tree and field crops in that county, but to date these losses have been more than compensated by increases in the sales of dairy and poultry products. Zoning restrictions connected with increasing urbanization are forcing the retirement of dairy herds and poultry flocks to outlying locations, sometimes in adjacent counties. The effect of urbanization on agriculture thus has been marked by a shift from crops to livestock, a factor of intensification that has more than made good the value of the land transgressed upon by expanding cities.

The areas included in the towns and cities of southern California are filled mainly by single-family dwelling units. This feature is related to the relatively small size of commercial cores in contrast to the multiplicity of neighborhood shopping districts, the ubiquitous automobile in contrast to the dearth of effective public transportation, and the generally wide scattering of public buildings such as schools, churches, and the offices of City, County, and State. The central area of Los Angeles is the closest counterpart to an eastern city, with a high silhouette (although earthquake hazards limit most buildings to 12 stories), numerous apartment houses and hotels, and a commercial core complete with shopping, industrial, and warehouse districts.

Even in Los Angeles, however, a scattered aspect predominates. The Los Angeles industrial district is now the third most productive


NEVADA
PACIFIC OCEAN
MEXICO
LEGEND
Urban areas
Places of 25,000
Places of 10,000 to 25,000
Places of 2,500 to 10,000
Places of 1,000 to 2,500
500 persons (outside places of 1000 or more)

Source: Map, U. S. Bureau of the Census

FIGURE 7. Distribution of population in southern California, 1950.

industrial center of the United States, but its 10,000 enterprises are widely distributed over Los Angeles County, Orange County, and parts of San Bernardino County. The chief industries—aircraft, motion pictures, food, fabricated metal products, machinery, clothing, and petroleum refining, in that order of magnitude—have unlike requirements for space, site, raw materials, power, and labor. This diversity is shown in the far-flung pattern of industrial development.

Those enterprises with high freight bills, such as iron and steel, food processing, and fabrication in heavy metals, are congregated along axes provided by the rail lines of the region, chiefly in areas south and east of the center of Los Angeles. Motion picture and aviation enterprises have not been tied to rail lines, but have been located in areas that formerly were suburban and hence contained large tracts of low-cost land, generally to the west of Los Angeles proper. Significant aircraft production also appears in San Diego, 100 miles south of Los Angeles.

The clothing industry has neither the necessity for handling materials in bulk nor a requirement for extensive grounds, and so occupies many small shops, most of which are within the metropolitan region of Los Angeles. Petroleum refining has been established near the major sources of oil, and the largest fields by far in southern California are in the area between the north edge of Los Angeles and the coast to the south. And finally, diversified light manufactures of many kinds are scattered throughout the towns and cities of southern California.

The annual dollar value added by manufacture in southern California is about $2 billion, as compared with $600 million from the sales of all farm products. Each succeeding year tends to widen the gap between manufacture and agriculture, as a result of the disproportionate rate of growth of cities as compared to rural areas in southern California.

The importance of this population factor in the economy of southern California can be seen from the map of population distribution (fig. 7). Despite the emphasis that has been placed upon the dispersed nature of land use, even in cities, the map indicates that some coastal basins are very much more densely settled than others, and that beyond the coastal mountains settlement nowhere attains the density that it has reached in the Los Angeles area. Obviously, climate, soil, water supply, and terrain have strongly affected the manner in which the region has been developed. Further, the urban factor is so strong that in Los Angeles County 97.5 percent of the population was classed as urban in the 1950 census. Specified in terms of city population growth, Los Angeles city increased from about 100,000 to nearly 2,000,000 in the period 1900-1949; in the same period of time San Diego grew from about 2,500 to more than 300,000. During this 50-year period, the population of the State as a whole increased, in round numbers, from 1,500,000 to 10,500,000, which indicates a much smaller factor of growth. Clearly most people have gone to the cities during the impressive wave of migration to California in the first half of the twentieth century.

Rapid city growth probably has brought about few major changes in the basic distribution of people and in the land uses of rural regions. This growth has taken place mainly in centers established before 1900, and much of it has represented internal development. Expansion of urbanized areas has taken place, to be sure, and has led to the pre-emption of land that formerly was farmed, but the total area so affected is small in comparison to the total acreage in farms.

More important to agriculture have been the increasing demands of Cailfornia's own urban markets, as shown by the previously mentioned change in the vicinity of Los Angeles, where dairy and poultry products, rather than the more widely publicized orchard crops, have become chief items of production. Urban centers also have controlled to a major degree the orientation of routes of transport, and the amount of traffic upon them. Thus, to the air traveller the most conspicuous landmarks over large parts of the desert are highways and railroads, rather than settlements or structures related to extensive grazing or irrigated agriculture (fig. 6). Many desert settlements receive important sources of income from transient traffic originating from, or destined for, the heavily populated coastal areas. Likewise conspicuous along the desert fringe close to the coastal mountains are towns and subdivisions that serve chiefly as winter resorts for coastal residents.

The land use of southern California's mountain areas also has been determined mainly by the needs of the highly developed urban areas nearby. Many large cities of the region are located on sites that might be termed natural debris basins for the detritus brought by streams originating in adjacent uplands. To minimize the chances for destructive flood runoff, protection of the natural cover of vegetation in mountain areas has been the chief objective of policies enforced by the U. S. Forest Service. As a consequence, roads and firebreaks are conspicuous in southern California's mountains. The provision of picnic and camp grounds and the development of mountain resorts, both on public and on private lands, are related largely to the demand created by the urban population.

It is inescapable that cities and towns should play an important part in the future of southern California. They serve as foci of economic and cultural life, and there is every reason to think that future expansions of population will take place mainly in the urban centers that are now well established. The most likely outlook for 50 years ahead would preserve the essential features of the distribution of population in 1950, even though expressed in greater numbers, and the same outlook also would preserve present major land uses in rural regions, although they might well be more intense and diverse than at present. The reasons for this relatively conservative prospect involve the belief that present land uses are well suited to the physical environment. Changes of the future probably will be made largely in response to influences originating elsewhere, and they may well be accomplished in a gradual and orderly fashion, as suggested above.

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3. INDIAN OCCUPATION IN SOUTHERN CALIFORNIA

By Robert F. Heizer *

The prehistoric peoples of the southern California region are notable, among California Indians, for many reasons. The most ancient cultures thus far found in the State once flourished in what is now the arid interior desert, on the shores of late glacial and early postglacial lakes that now are dry. The only maritime Indians of the State, the Chumash tribe, lived on the Santa Barbara mainland and offshore islands, and the only natives with an agricultural economy in California were those southerners whose homes lay along the banks of the mighty Colorado River. The pottery-making art was chiefly practiced by southern California tribes. These broad differences, together with a host of minor ones, have led anthropologists to set the southern California region off from the central and northern portions of the State as exhibiting a distinctive type, stamp, or pattern of native civilization (Kroeber, 1925, Chap. 59).

The southern California Indians spoke dialects of several languages. Chumash speech was a member of the Hokan family, to which also belong the variants of Diegueno, Kamia, Mohave, Halchidhoma, and Yuma. The Yokuts tribe spoke a language of the Penutian family, which in California is restricted to the central portion of the State. The remainder of southern California tribes spoke languages of the stock called Shoshonean or Uto-Aztecan, a far-flung family known from Wyoming in the north to the Valley of Mexico in the far south. It therefore seems that anciently, as now, the population of California was of diverse origin.

In the most ancient past in terms of man's occupation of California (and geologists hardly will be impressed by the time involved), the peoples had a simple cultural equipment and subsisted largely by hunting and gathering wild vegetal foods. They lived, toward the waning of the last glacial period (about 9,000 years ago), around such extensive freshwater pluvial lakes as Lake Mojave, Silver Lake, and the lake in the Pinto Basin. No evidence of permanent habitation has been found, and it is supposed that these early Californians were wandering nomads. The subject of postglacial archaeological dating and ancient cultures is treated in detail elsewhere (Antevs, 1952; Heizer, 1952). Another ancient find is that of "Los Angeles Man," a human skelton found deeply buried in late Pleistocene deposits and not far from the remains of Imperial elephant (*Archidiskodon*). These human bones probably are the oldest human remains from the western states (Clements, 1938; Heizer and Cook, 1952).

From later times there are more varied and abundant archaeological remains from the coast and desert areas, and it is probable that most of these are ascribable to the ancestors of the recent Indians of southern California. These later peoples, whose antiquity is not believed to exceed 2,000 years, lived on the ocean front, the coastal plain, or in the intermontane valleys where fresh water was available, and subsisted by fishing and hunting, and the eating of

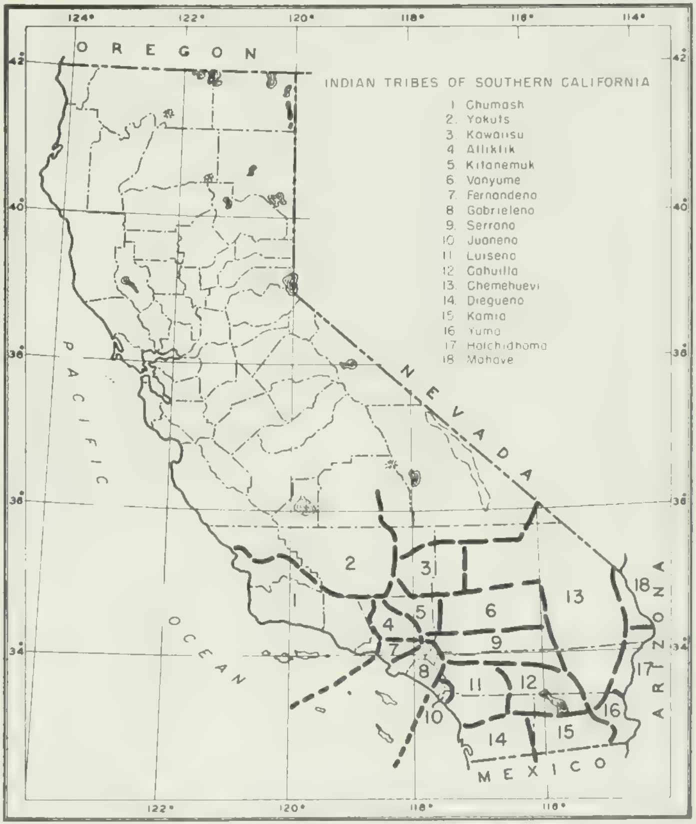

Figure 1. Indian tribes of southern California.

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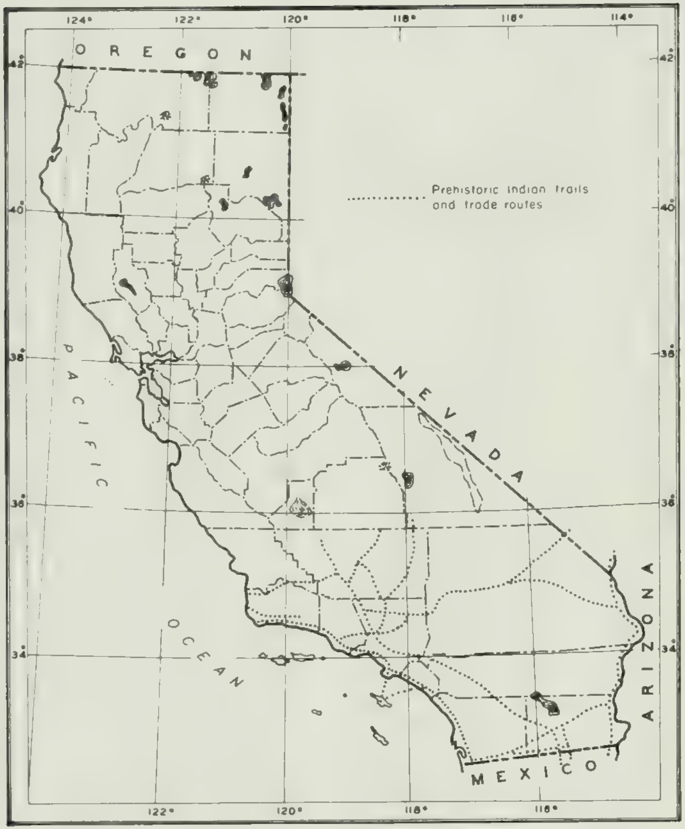

Figure 2. Indian trails and trade routes in southern California.

acorns and grass seeds. Our earliest records of these tribes come from the journals of the Spanish exploring expeditions of Cabrillo (1542), Vizcaino (1602), and Portola (1769). The Indians are described as happy, friendly, and numerous. Beginning in 1769, the Franciscan padres established nine missions in which the Indians were converted not only to a new religion, but also to a new way of life. In 1834 the missions were secularized, and the handful of survivors of once populous tribes were allowed to go once more their own way.

Certain general culture traits were widespread among the tribes living in southern California at the coming of the Spaniards in the eighteenth century. Dress was scanty, women wearing a fringed apron and men either going naked or donning a loincloth. In the dry interior desert, where the white man would see little to sustain him, the ingenious natives recognized more than 60 edible plants and managed to extract a reasonably good living. Rabbits, which furnished the bulk of meat food, were taken with a flat boomerang-like throwing club. Excellent basketry, red pottery, and a variety of stone utensils were employed in gathering and cooking activities. A rich ceremonial system had been developed, and one feature of this was the drinking of an infusion of a sacred narcotic root commonly called Jimsonweed (*Datura metaloides*) during the initiation of boys into adult status. The dead were cremated, and the ashes were buried in pottery jars.

To geologists, the most interesting aspect of California Indian life may well be the exploitation of rocks and minerals by these uncivilized peoples. A survey of California Indian mines and quarries already has been published (Heizer and Treganza, 1944), and the following data are abstracted from this more detailed report. In the southern California area two mineral deposits were scenes of notably large-scale quarrying operations. One of these was the steatite deposit on Santa Catalina Island, about 10 miles northwest of the main island town of Avalon. The quarries were discovered in 1876 by P. Schumacher (1878), an archaeologist employed by the Smithsonian Institution, although Spanish explorers of the late eighteenth century had mentioned the island as the source of the globular stone bowls seen by them in the Gabrieleno and Chumash mainland villages. Chisels of hard slate were used to work the soft steatite so that a globular mass, attached by a small pedestal, was gouged out, hollowed roughly, broken off, and then finished by rubbing the surface with flat sandstone files. The finished vessels were then transported in plank canoes across the channel to mainland towns at Redondo and San Pedro, which were the retail distributing points for this commodity.

The other notable prehistoric quarry area was the source of turquois in the Mojave Sink region of San Bernardino County, near the main highway from Barstow to Las Vegas. The quarries were first described in 1898 by Gustav Eisen, a prominent member of the California Academy of Sciences. More recently M. J. Rogers of the San Diego Museum has published the results of a careful archaeological survey of the quarry area (Rogers, 1929; Dunn, 1930). The turquois mines were not worked by the simple local resident peoples, the Chemehuevi tribe, but by more culturally advanced outlanders known as the Pueblo peoples of Arizona and New Mexico, who made expeditions in force to the turquois localities to extract the green stone considered by them to be of high value. This fact is

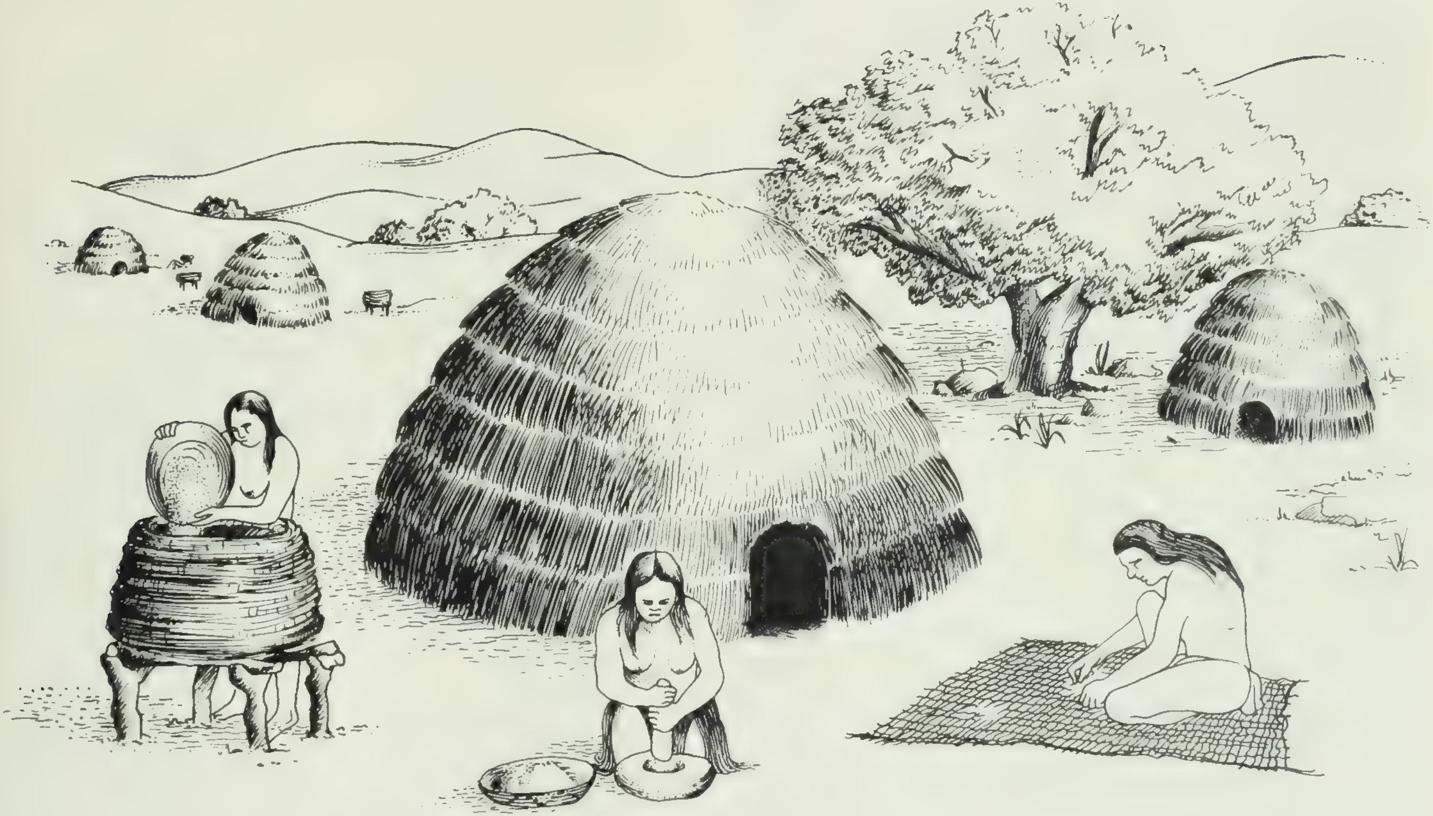

FIGURE 3. Village scene among prehistoric southern California Indians (after Underhill).

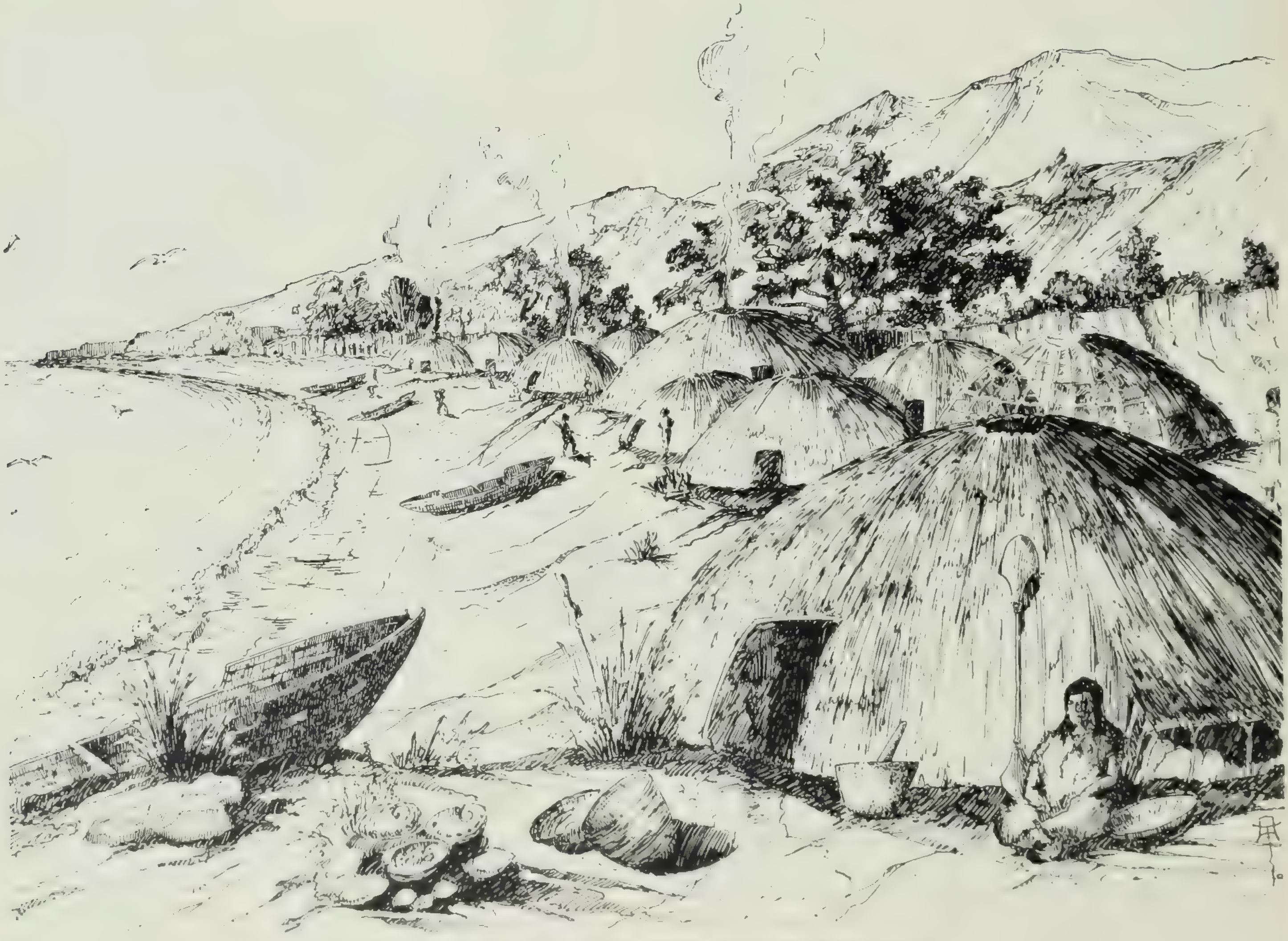

FIGURE 4. Reconstruction of a Chumash village of the Santa Barbara coast.

made clear by the presence at the quarries of painted pottery, grooved stone axes, and mauls of types distinctive to the Puebloan peoples across the Colorado River to the south and east. The principal ancient quarry pit, at what is now known as the Himalaya mine in T. 16 N., R. 11 E., was 30 feet long, 12 feet wide, and 12 feet deep.

Raw materials less intensively exploited, or which occur in scattered localities, include various deposits of residual weathered granite, which served as the clay for pottery making (San Diego and Imperial Counties); obsidian, which was chipped into knives and arrowpoints (Ventura County); hematite, limonite, and manganese for body paint (San Diego and Imperial Counties); and asphaltum, which was used as an adhesive and for waterproofing baskets or caulking plank canoes (Santa Barbara, Ventura, and Los Angeles Counties), as discussed by Heizer (1940).

The famous tourmaline mines near Mesa Grande, San Diego County, were first worked by Indians as proved by the presence of these gems in prehistoric graves and by the traditional use of tourmaline crystals in some of the sacred Indian ceremonies.

Communication among the Indians was by foot, there being in prehistoric times no domesticated pack or riding animals. Travel was by well-defined trails along the coast and across the desert from one waterhole to another. A lively exchange of Puebloan woven blankets was carried out by the Colorado River Mohave Indians with the coastal peoples for abalone and other marine shells, which were prized by the interior tribes for ornaments and beads. The courses of some of these trails are known, and are shown on the accompanying map.

In certain areas on cliff or boulder faces, elaborate designs were painted or pecked (Steward, 1929). Painted designs (pictographs) usually were done in red hematite on a light rock surface; pecked designs (petroglyphs) commonly were made on darker rocks, where the pecked lines penetrated to the contrasting lighter colored, unweathered stone. Along the Colorado River are the curious "boulder pictographs," which consist of immense intaglio figures of animals, man, spirals, etc., formed by removing the desert pavement to expose the light colored sandy soil beneath. These recently have been described by F. Setzler (1952) and by M. Harner (1953).

FIGURE 5. Chumash Indian couple. Courtesy Santa Barbara Museum of Natural History.

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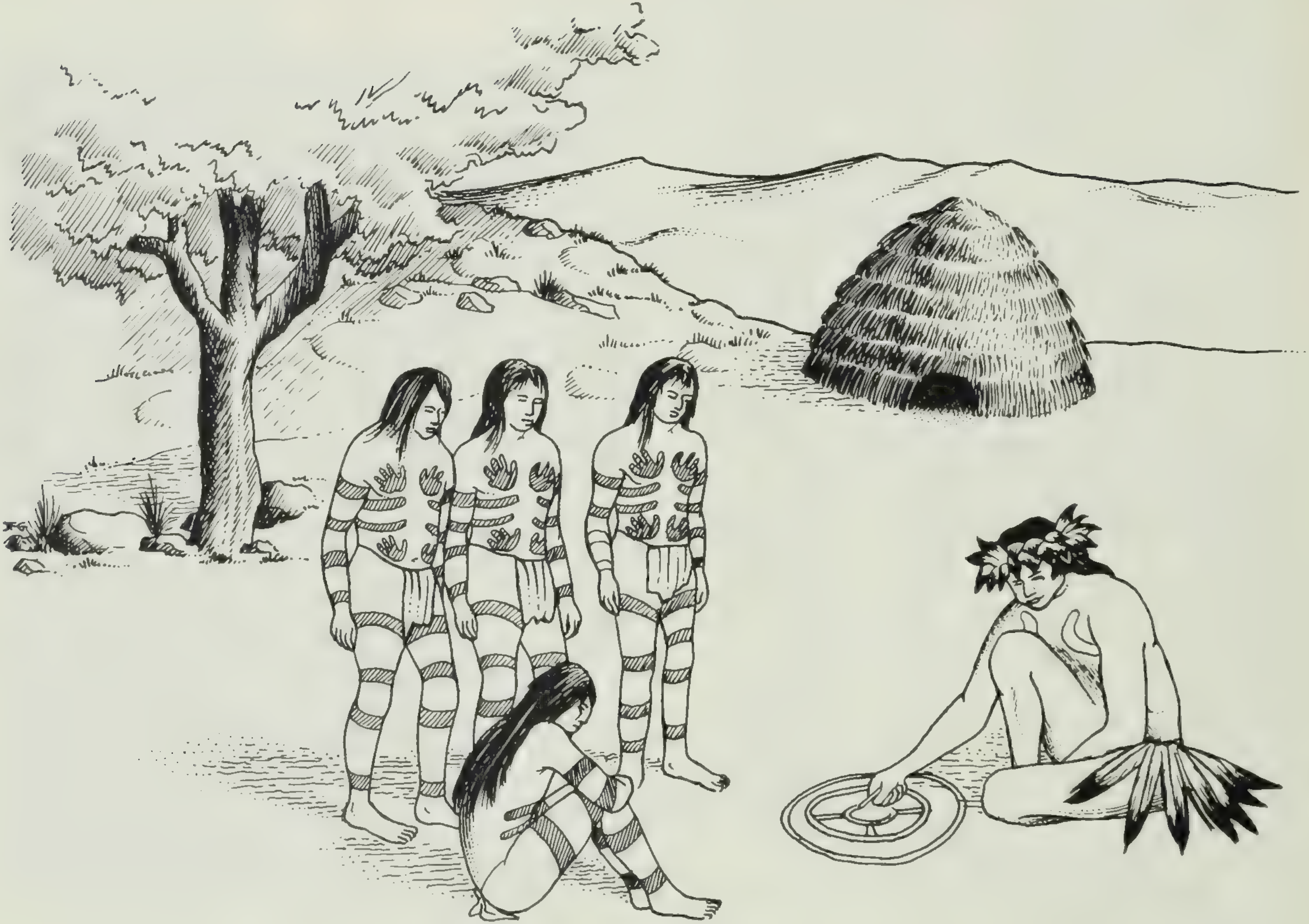

FIGURE 6. Luiseno priest making a "sand painting" in boys' initiation ceremony.

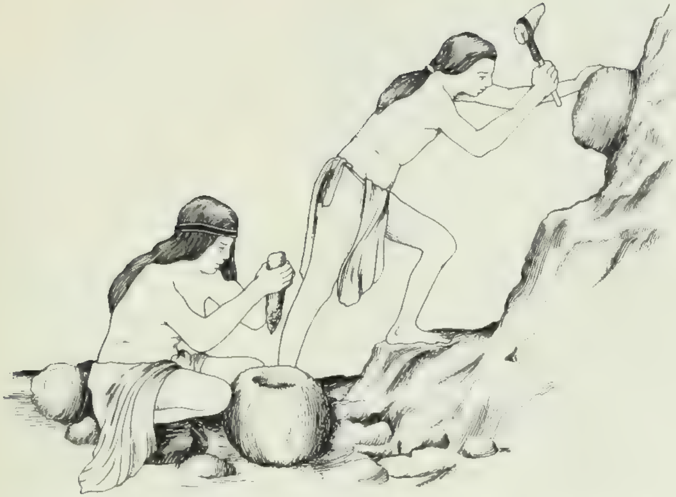

FIGURE 7. Steatite quarrying and bowl making on Santa Catalina Island.

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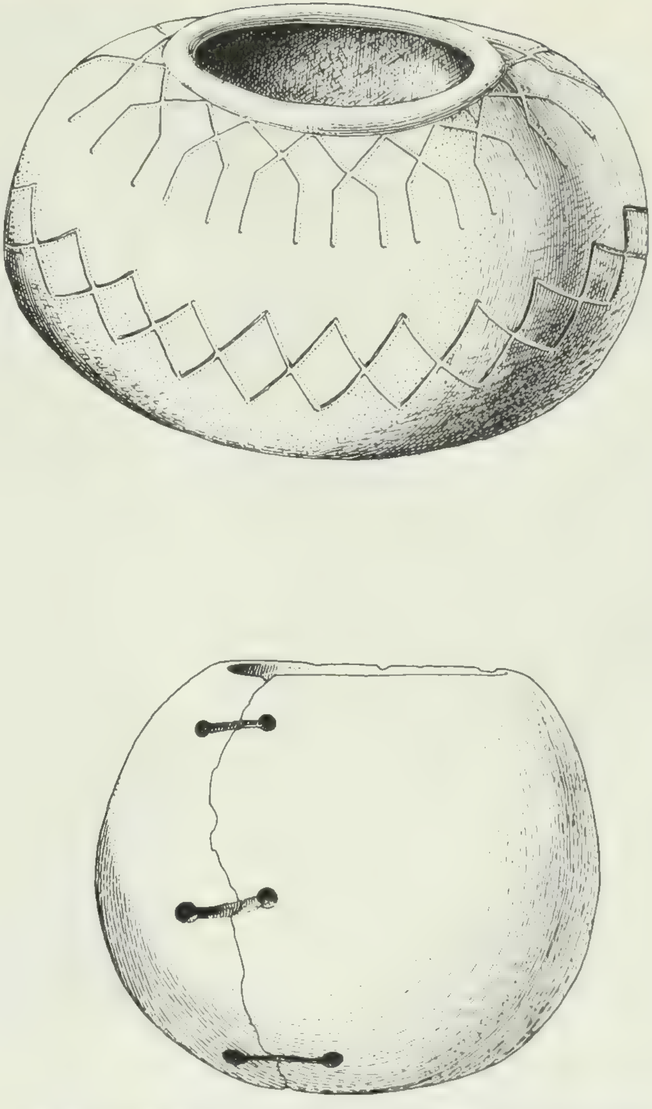

FIGURE 8. Steatite bowls. Above: bowl with incised decoration, ⅓ scale. Below: broken bowl showing ancient method of mending by crack lacing, ⅙ scale.

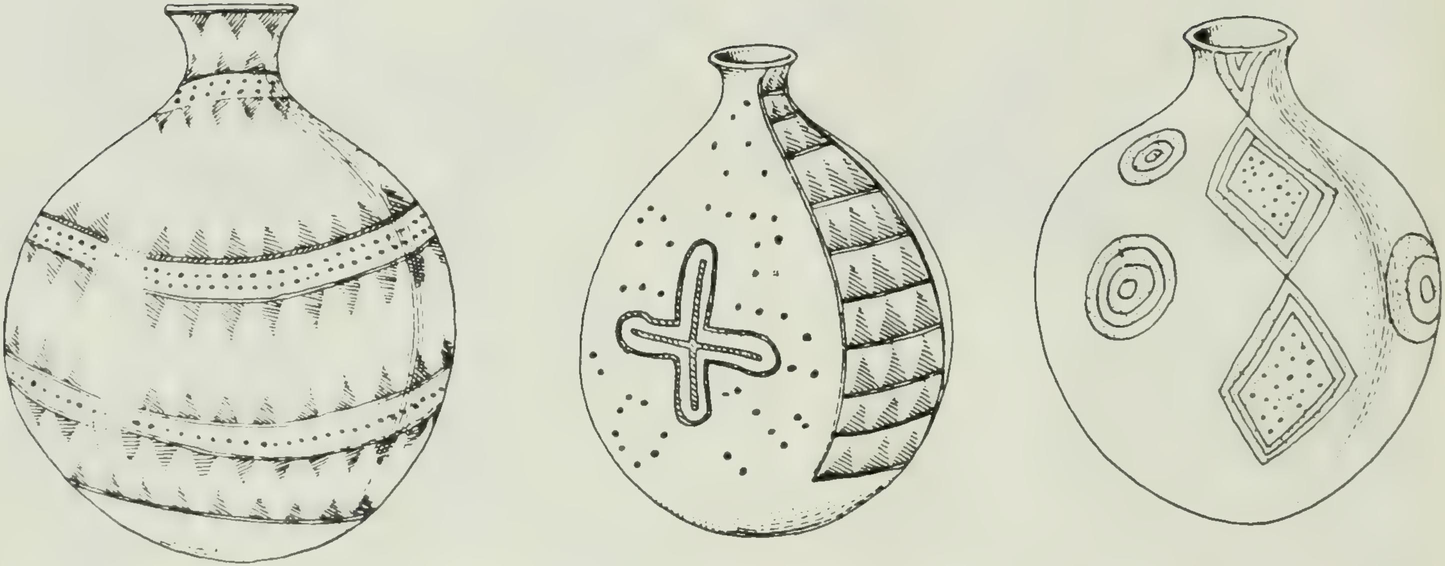

FIGURE 9. Prehistoric pottery vessels from Twentynine Palms region.

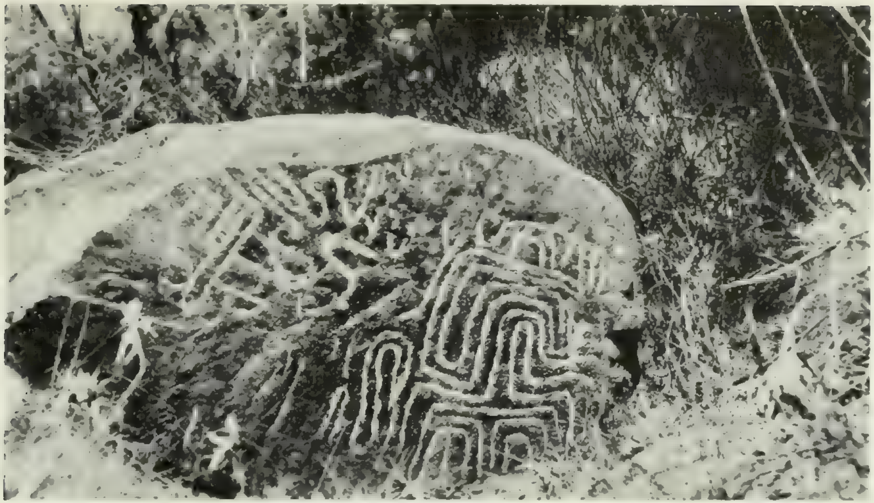

Figure 10. Petroglyphs. Above: design on boulder, Orange County. Below: pecked "maze" on boulder, Riverside County.

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BULLETIN 170

CHAPTER II

GEOLOGY OF THE NATURAL PROVINCES

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Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER II

GEOLOGY OF THE NATURAL PROVINCES

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Editorial Note:

CHAPTER TWO deals with the geologic features of ten natural provinces of southern California, and thus constitutes a general summary for the region as a whole. Each of these provinces has characteristic assemblages of structural and stratigraphic features, rock types and mineral deposits, and geomorphic relationships that reflect a complex geologic history. Each, too, presents a wide variety of problems, many of which will stimulate, provoke, and even frustrate geologists for years to come. The composite section for the entire region is an unusually complete one, however, and ultimately it will yield up much of the information that is needed for a fuller presentation of southern California geology than the one made in this volume.

The ten contributions in this chapter are intended to provide the reader with a background of general data and broad geological relationships, some of which are unusual or even appear to be unique to this region. Many of them are discussed in greater detail in subsequent chapters. The provinces are described in a geographic order, beginning with the vast Mojave Desert region and progressing in a general clockwise direction southward, westward, and thence northwestward through the coastal region before closing the traverse in an eastward direction.

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1. GENERAL GEOLOGY OF THE MOJAVE DESERT REGION, CALIFORNIA*

By D. F. Hewett †

INTRODUCTION

The Mojave Desert region, commonly known by the briefer term, Mojave region, occupies a large part of southern California. For the purposes of this report, the limits of the region are essentially those adopted by Thompson (1929). The northwestern boundary is the Tehachapi Mountains, or roughly the Garlock fault. The southwestern boundary, a group of ranges that includes the Sierra Pelona, the San Gabriel Mountains, and the San Bernardino Mountains, roughly coincides with the San Andreas fault west of Cajon Pass. No distinct, persistent physiographic feature forms the northern boundary, although the Garlock fault defines it as far eastward as the Death Valley trough; the writer follows Thompson (1929) in using the 36th parallel eastward from the Sierra Nevada as far as the Colorado River. For the eastern boundary, the Colorado River seems better than the 115th meridian. These limits on the east and northeast depart from those proposed by Baker (1911), which are the divides from which the drainage is generally east and northeast to the Colorado River.

The name "Mojave block" is applied to the part of the Mojave region that lies north of the San Andreas fault on the west and the San Bernardino Mountains on the east, and south of the Garlock fault. The eastern limits of the block cannot be defined until the course of the Garlock fault southeast of the Soda Mountains is known. As will appear later, the surface and structural features of the Mojave block differ greatly from those in the areas both north and south of it.

The term "basin" is herein applied to a block of sediments, especially those of Tertiary age, that are now preserved in downwarps (synclines) or monoclines. The Barstow basin (Barstow syncline) and Calico basin are excellent examples. The term "trough" is applied to certain major valleys of the region, such as Death Valley trough, Barstow-Bristol trough, and Leach trough.

The areas within the Mojave region for which geologic work has yielded geologic maps are shown in figure 1. Geographic features of this region that are mentioned in the following paragraphs are shown in figure 2.

At present, the most comprehensive geologic map of the Mojave region is that compiled by O. P. Jenkins and published by the California Division of Mines in 1938, at a scale of 1:500,000. An earlier map accompanies the report of D. G. Thompson (1929) on the water resources of the region; even though it was published 25 years ago, this map has considerable merit. A present vigorous program of geologic work by the U. S. Geological Survey should yield a new geologic map of the region within a few years.

ACKNOWLEDGMENTS

In preparing the present paper, the author has consulted most of the published reports that describe the features of the region, and all of those that appear in the list of references. In addition, numerous workers in the region have most kindly placed at his disposal much unpublished material, mostly now in process of publication. The author also has had access to the product of recent geologic investigations by members of the staff of the U. S. Geological Survey, now assigned to the Claremont office of the Survey. If, in using this material, the author has made interpretations that differ from those of the geologists who collected it, he alone is responsible.

The author acknowledges, and with much appreciation, the benefits of conferences and field trips with the late Chester Stock, the late Hoyt S. Gale, Oliver E. Bowen, Jr., Thane H. McCulloh, Mason L. Hill, John S. Shelton, and members of the Survey staff, especially Ward C. Smith, Kenneth E. Lohman, Donald H. Kupfer, George I. Smith, Siegfried J. Muessig, Thomas W. Dibblee, Jr., and Frank M. Byers, Jr.

SURFACE FEATURES

All of the region under consideration lies between longitude 119°00′ on the west and the Colorado River, roughly longitude 115°00′, on the east. It extends southward from latitude 36°00′ to points as far as latitude 34°00′. To facilitate description, four parts of the Mojave region will be recognized herein: (1) the northeastern part, which lies east of longitude 117°00′ and north of latitude 35°00′; (2) the southeastern part, east of longitude 117°00′ and south of latitude 35°00′; (3) the southwestern part, which extends west from longitude 117°00′ and south from latitude 35°00′; and (4) the northwestern part, which lies west of longitude 117°00′ and north of latitude 35°00′ (figs. 1, 2).

The surface features of the Mojave block differ greatly from those of the areas that lie north and south of it. The western part of the block, or the part that lies west of longitude 117°00′, south of the

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* Publication authorized by the Director, U. S. Geological Survey. The stratigraphic nomenclature is not, in some cases, that officially adopted for use by the Geological Survey.

† Staff Scientist, U. S. Geological Survey, Pasadena.

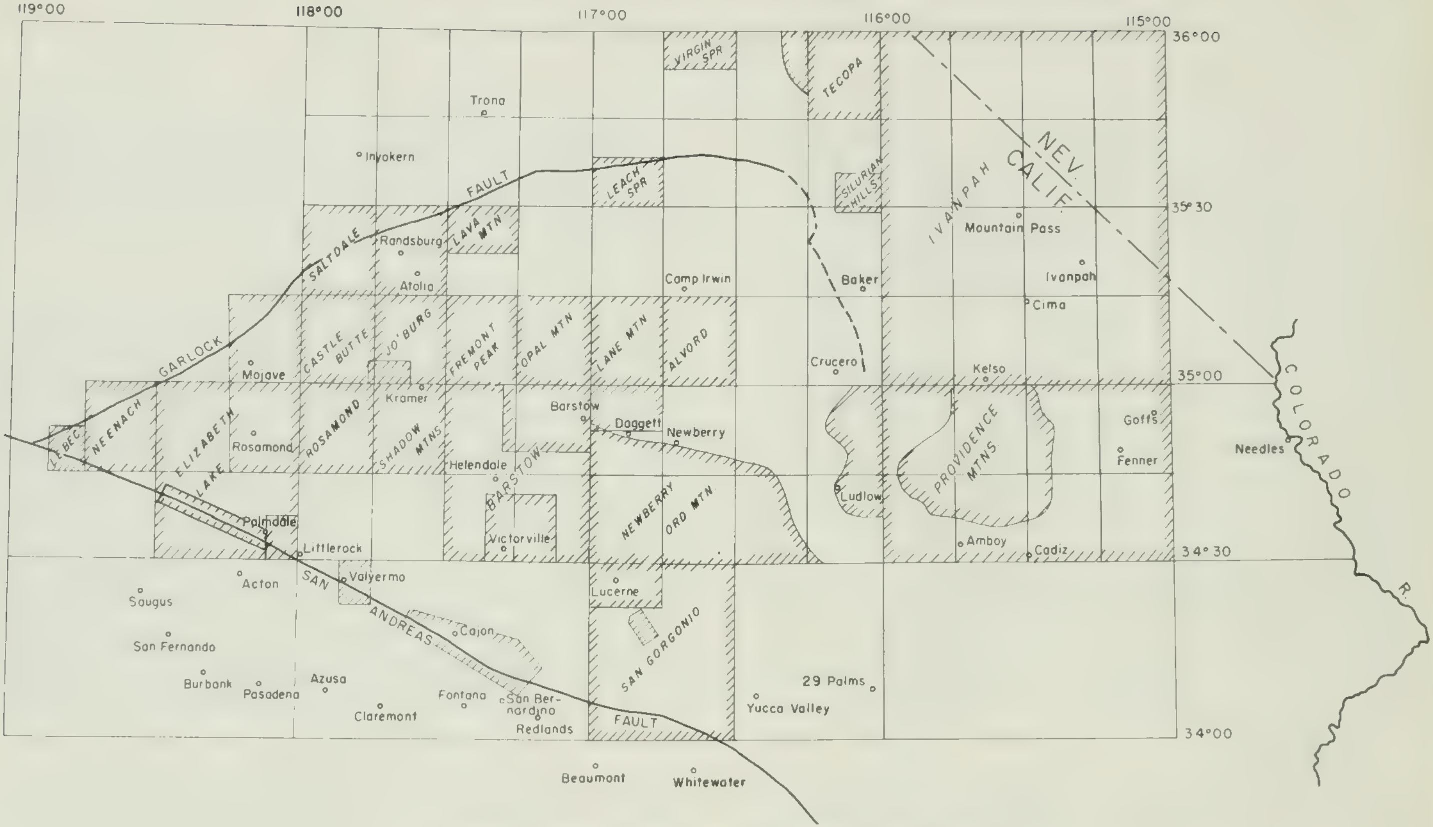

FIGURE 1. Index of geologic maps in the Mojave Desert region.

Garlock fault, and north of the San Andreas fault, is a plain that slopes gently eastward from Mojave (elevation 2,750 feet) to Barstow (elevation 2,105 feet). Rising above this plain are numerous isolated hills, such as Castle Butte (elevation 3,145 feet) and Black Butte (elevation 3,684 feet), in addition to ridges and local mountain masses such as Soledad Mountain (elevation 4,183 feet), Fremont Peak (elevation 4,604 feet), Red Mountain (elevation 5,270 feet), and Shadow Mountains (elevation 4,039 feet).

Parts of this plain are smooth surfaces of rock with a sparse cover of local debris (pediments), but large parts are underlain by alluvium, within broad areas of which there are several large playas, or dry lakes. Among these are Rosamond (2,271 feet), Rogers (Muroc) (2,271 feet), Mirage (2,334 feet), and many smaller playas. The plain is limited by the Tehachapi and El Paso Mountains north of the Garlock fault and by the Liebre, Pelona, and parts of the San Gabriel Mountains south of the San Andreas fault. East of Barstow, and within the Mojave block, are higher and more numerous isolated mountain masses and linear ridges, mostly disposed without apparent pattern. Among these are the Calico Mountains (elevation 4,520 feet), Ord Mountains (elevation 6,250 feet), Bristol Mountains (elevation 3,600 feet), Old Woman Mountains (elevation 5,300 feet), and Turtle Mountains (elevation 4,200 feet). A few mountains are long, linear ridges that trend mostly northwest; the Bullion Mountains (elevation 4,600 feet) and Sheep Hole Mountains (elevation 4,500 feet) are good examples.

North of Leach trough, the valley that persistently follows the Garlock fault, is a vast area in which northward-trending ranges are separated by persistent deep valleys. Among these ranges are the Argus (elevation 6,562 feet), Slate (elevation 5,093 feet), Panamint (elevation 11,045 feet), Black (elevation 6,384 feet), and Spring (elevation 11,910 feet). East of the Death Valley trough and its southern extension, the valley occupied by Silver Lake and Soda Lake, most of the mountains are linear and trend north. These include the Old Dad Mountains (elevation 4,275 feet), New York Mountains (elevation 7,445 feet), and Providence Mountains (elevation 6,900 feet). The San Bernardino and Little San Bernardino Mountains (maximum elevations, 11,485 feet and 6,000 feet, respectively) are regarded as the limits of the Mojave Desert region, even though they lie north of the San Andreas fault.

East and west of Barstow are broad, linear valleys, most of which contain playas whose elevations are successively lower eastward. These dry lakes include, in eastward succession, Troy (elevation 1,800 feet), Soda (elevation 1,000 feet), Bristol (elevation 600 feet), Cadiz (elevation 600 feet), Danby (elevation 600 feet), and Chuckawalla (elevation 500 feet). An exception to this trend in levels is Ivanpah Valley (elevation 2,500 feet), for which there is an exceptional explanation.

GEOLOGY

Pre-Cambrian Rocks

Lower Pre-Cambrian Crystalline Rocks. Upper pre-Cambrian or basal Paleozoic sedimentary rocks can be seen to rest upon older crystalline rocks in only a few places in the Mojave region. In many other places an early pre-Cambrian age is inferred for the crystalline rocks solely on the basis of their degree of metamorphism, and hence this age assignment must be regarded as tentative. It also should be pointed out that the absence of high degrees of metamorphism does not necessarily indicate post-Cambrian age.

Proven upper pre-Cambrian and basal Paleozoic rocks can be observed resting upon older metamorphic rocks only in the northeastern part of the Mojave region. At the present time, in the entire Mojave block, beds assuredly representing the base of the Paleozoic system are not known anywhere. On the north slope of the Kingston Range, in the northwest corner of the Ivanpah quadrangle, are upper pre-Cambrian sedimentary rocks, the Pahrump series, that attain a maximum thickness of about 7,000 feet and rest upon granite gneiss. At several other places in the Ivanpah quadrangle, basal Paleozoic formations, the Prospect Mountain quartzite and the Tapeats sandstone, rest upon granite gneiss in the low hills 3 miles northwest of Kelso, at the northeast end of the Old Dad Mountains, and on the south slope of Sheep Mountain, near Jean, Nevada (Hewett, 1954).

In the region east of Ludlow and south of the Providence Mountains, the work of Miller (1946) and Hazzard and Dosch (1937) indicates that four successive rock units can be differentiated: (1) the oldest, the Essex series of the Old Woman and Piute Mountains, consisting of quartz-biotite gneiss, marble, quartzite, mica schist, and hornblende schist, and regarded as metasediments; (2) intermediate to basic intrusive rocks, ranging from quartz diorite to gabbro; (3) the Fenner gneiss and related intrusive rocks; and (4) the Kilbeck gneiss and the Palms granite near Twentynine Palms (Miller, 1938). These four units or formations are grouped by Miller in the Needles complex.

In the Newberry-Ord Mountains area, southeast of Barstow, Gardner (1941) recognized a lower pre-Cambrian assemblage of metasedimentary rocks, chiefly granite gneiss and marble, intruded by diorite gneiss and granite porphyry.

On the basis of their advanced degree of metamorphism, rocks in parts of the central and western Mojave region are interpreted by the writer and others as lower pre-Cambrian. These include the injection gneiss of Tiefort Mountain, east of Camp Irwin, and the granite gneiss of the "turtlebacks" of the Black Mountains, east of Death Valley (Curry, 1949; see also Contribution 7, Chapter IV).

In summary, where detailed studies have been made in appropriate areas, at least three (and, in places, four) units of lower pre-Cambrian crystalline rocks can be recognized: (1) early metasedimentary rocks; (2) diorite and meta-diorite; and (3) granite and meta-granite. Each of these units shows lit-par-lit injection and is highly foliated over most of the region.

Upper Pre-Cambrian Rocks. At several localities in the western Mojave region, rock units have been considered to be late pre-Cambrian in age on the basis of slight degree of metamorphism, but only at a few localities in the north-central part of the region have such rocks been observed to underlie known basal Paleozoic sedimentary rocks. In the Kingston Range (Hewett, 1954), the Pahrump series is made up of three formations, Crystal Spring, Beck Spring, and Kingston Peak, aggregating about 7,000 feet. This series rests upon granite gneiss and is unconformably overlain by the Noonday dolomite, the basal formation of the Paleozoic system in this area. The basal formation of the Pahrump series, Crystal Spring, shows 500 feet or more of conglomerate at the base, overlain by alternating green and red shale and dolomite. The Beck Spring dolomite is

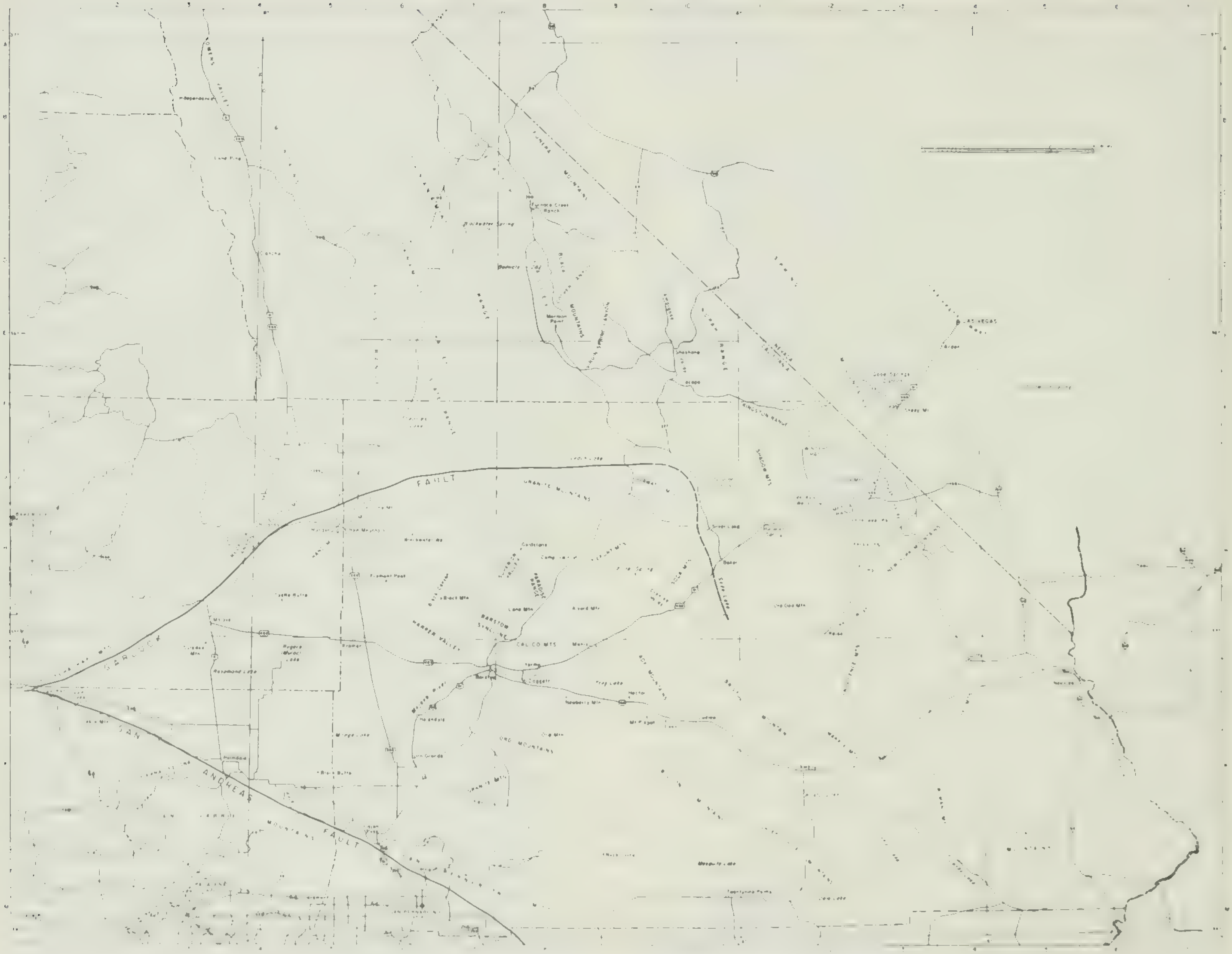

FIGURE 2. Index map showing geographic features in the Mojave Desert region.

wholly thin-bedded gray dolomite, 1,100 to 1,200 feet thick. The Kingston Peak formation is sandstone, shale, and conglomerate, and attains a maximum thickness of 4,000 feet. These three formations have been found in the Tecopa area by Mason (1948) and in the Silurian Hills by Kupfer (1952).

In several parts of the western Mojave region, a late pre-Cambrian age has been assigned to the Pelona schist, estimated to be 7,000 feet thick (Simpson, 1934), to the Rand schist in the Rand Mountains (Hulin, 1925), and to the Mesquite schist in the El Paso Mountains (Dibblee, 1952).

In summary, upper pre-Cambrian sedimentary rocks, in an advanced state of metamorphism, are sporadically distributed in the western third of the Mojave block and in the nearby mountains to the north and south. A thick section of sedimentary rocks of diverse types, the Pahrump series, is widely distributed in the northeastern part of the Mojave region, and meagre information indicates that it probably exists in and beyond the Panamint Range; these rocks, however, do not show the advanced state of metamorphism that characterizes the Pelona, Rand, and Mesquite schists farther west and southwest.

In a few places, especially on the northeastern slopes of the Kingston Range, a pronounced unconformity separates the Pahrump series from the overlying Paleozoic sedimentary rocks.

List of geographic names on map, figure 2.

Alvord Mt.	9-I
Amargosa Valley	10-E
Amboy	12-K
Arden, Nevada	14-E
Argus Range	6-E
Avawatz Mts.	10-G
Badwater	8-D
Baker	10-H
Barstow	7-J
Barstow Syncline	7-I
Bitter Spring	9-H
Black Butte	5-K
Black Canyon	6-I
Black Mt.	7-I
Black Mts.	8-D
Blackwater Spring	7-D
Blackwater Well	6-H
Bristol Lake	12-K
Bristol Mts.	11-J
Bullion Mts.	10-K
Cadiz Lake	13-L
Cady Mts.	9-J
Cajon Pass	6-L
Calico Mts.	8-I
Camp Irwin	8-H
Castle Butte	4-I
Cima	12-H
Clark Mt.	12-G
Colorado River	16-K
Copper Canyon	8-D
Cottonwood Spring	15-F
Cronise Valley	10-I
Daggett	8-J
Dale Lake	12-M
Danby Lake	14-L
Death Valley	8-D
Dome Mt.	6-G
El Paso Mts.	4-G
Fremont Peak	6-H
Funeral Mts.	8-C
Garlock Fault	2-J
Goffs	14-J
Goldstone	8-H
Goodsprings District	13-F
Gorman	1-J
Granite Mts.	8-G
Halloran Spring	11-H
Harper Valley	6-I
Hector	9-J
Helendale	6-J
Independence	3-B
Inyo Mts.	4-B
Ivanpah Valley	13-G
Jean	13-F
Kelso	12-I
Kelso Wash	12-I
Kessler Peak	12-H
Kingston Range	11-F
Kokoweef Peak	12-H
Kramer	5-I
Las Vegas, Nevada	14-E
Las Vegas Wash	14-E
Lava Mts.	6-G
Lavic	10-J
Leach Lake	8-G
Liebre Mt.	2-J
Ludlow	10-J
Manix	9-I
Marble Mts.	12-K
Mescal Range	12-G
Mesquite Lake	10-L
Mirage Lake	5-K
Mojave	3-I
Mormon Point	8-E
Mt. Pisgah	9-J
Newberry Mt.	9-J
New York Mts.	13-H
Nopah Range	10-E
Old Dad Mt.	11-I
Old Woman Mts.	14-K
Ord Mts.	8-K
Oro Grande	6-K
Overton, Nevada	17-D
Owens Valley	3-A
Panamint Range	6-C
Panamint Valley	6-D
Paradise Range	8-I
Piute Mts.	14-J
Providence Mts.	12-J
Quail Lake	1-J
Redrock Canyon	4-H
Ricardo	4-H
Rock Corral	9-L
Rock Creek	4-K
Rogers (Muroc) Lake	4-J
Rosamond Lake	4-J
San Andreas Fault	3-K
San Bernardino Mts.	7-M
San Gabriel Mts.	3-L
Searles Lake	6-F
Shadow Mts.	11-G
Sheep Hole Mts.	11-L
Sheep Mt.	13-F
Sierra Pelona Ridge	3-K
Silurian Hills	10-G
Silver Lake	10-H
Slate Range	7-F
Soda Lake	11-I
Soda Mts.	10-H
Soledad Mt.	3-I
Spring Mts.	11-D
Superior Valley	8-H
Tehachapi Mts.	1-J
Tiefort Mts.	9 H
Twenty-nine Palms	11-M
Turtle Mts.	15-L
Valley Wells	12 G
Virgin Spring Canyon	9-E
Winters Pass	12-G
Yermo	8-J

Paleozoic Rocks

Thick sections of sedimentary rocks, which yield abundant fossils that indicate the presence of all systems of the Paleozoic, are found over large areas north of the Garlock fault and east of the Death Valley trough. In contrast, the Mojave block contains only a few widely scattered areas of Paleozoic rocks, and thus far these rocks have yielded very few fossils. Further, in the area north of the Garlock fault and eastward, carbonate rocks form a large part of the thick sections, whereas in the Mojave block carbonate rocks form a small part of the exposed sections and clastic sedimentary rocks are abundant. Again, in many places north of the Garlock fault and eastward, the basal beds of the Cambrian system rest upon a wide variety of sedimentary rocks (Pahrump series) and metamorphic rocks. Even though thick sections of sedimentary rocks occur in several places, beds that yield fossils older than Mississippian are not known to be exposed in the Mojave block.

Cambrian System. Sedimentary rocks of Cambrian age have been recognized and studied in the mountains which lie in the broad arc that extends eastward from the Panamint Range (Hopper, 1947) to the Tecopa area (Mason, 1948), the Nopah Range (Hazzard, 1938), Kingston Range (Hewett, 1954), Spring Mountains (Hewett, 1931), Providence Mountains (Hazzard and Crickmay, 1933; Hazzard and Mason, 1936), Bristol Mountains (Clark, 1921), and Marble Mountains (Riccio, 1952). Sedimentary rocks that have the lithology and general succession of known Cambrian rocks nearby, are also known near Johnnie, Nevada (Nolan, 1929).

As a result of this work, several conclusions can be stated:

(1) The section in the Nopah Range that has yielded good collections of Cambrian fossils is about 16,000 feet thick, and the thickness of similar beds decreases steadily eastward, so that in the Sheep Mountain area near Jean, Nevada, the section is not more than 2,000 feet thick.

(2) In the Nopah and nearby ranges, the basal member is the Noonday dolomite (Hazzard, 1938), which attains a maximum thickness of 2,000 feet on the north side of the Kingston Range (Hewett, 1954). It thins steadily eastward and is absent in the ranges south of Ivanpah Valley. It is present in the Panamint Range and probably farther northwestward, as well.

(3) The Noonday dolomite is succeeded by a thick section of mainly clastic sediments, comprising the Johnnie formation, Stirling quartzite, Wood Canyon formation, and Bright Angel shale. These attain thicknesses of 11,800 feet near Johnnie (Nolan, 1929) and 8,500 feet in the Nopah Range (Hazzard, 1938). From good fossil collections, it appears that the Wood Canyon formation is Lower Cambrian, and therefore that the underlying Noonday dolomite, Johnnie formation, and Stirling quartzite also are Lower Cambrian.

(4) In contrast, the thin section of clastic sediments near Sheep Mountain appears to be Middle Cambrian, so that the thick sections of the Johnnie area and Nopah Range clearly lie in a basin that did not extend far southeast.

(5) In the Nopah Range, the overlying Cadiz formation, Bonanza King formation, and the Cornfield Springs formation, which are largely carbonate rocks with small amounts of clastic sediments, are considered to be Middle Cambrian on the basis of meagre collections of fossils, found largely in the uppermost formation (Hazzard, 1938). These units attain a thickness of 5,200 feet in the Nopah Range, but the estimated thickness in the Providence Mountains is only 3,200 feet (Hazzard and Mason, 1936). These formations were not recognized at Sheep Mountain near Jean, Nevada, where the entire section of Cambrian, Ordovician, and Silurian units (Tapeats sandstone, Bright Angel shale, and Goodsprings dolomite) is only 2,900 feet thick.

(6) The sections of pre-Devonian sedimentary rocks tend to maintain uniform thicknesses, 2,500 to 3,000 feet, along northeast axes in the eastern Mojave region (Hewett, 1954).

Ordovician System. Only in the Nopah Range, and in nearby ranges in the northeastern part of the Mojave region, have beds that yield fossils assuredly of Ordovician age been found. In these ranges, Hazzard (1938) reports the presence of the Pogonip dolomite, the Eureka quartzite, and the Ely Springs dolomite, which aggregate 2,100 feet in thickness. The middle part of the Goodsprings dolomite in the Goodsprings district (Hewett, 1931) yielded a single fossil considered to be Ordovician.

Silurian System. Poorly preserved fossils in the section of the Nopah Range indicate the presence of about 335 feet of dolomite and chert of Silurian age (Hazzard, 1938). A new genus of sponge taken from near the top of the Goodsprings dolomite in the Spring Mountains (Hewett, 1931), also indicates that beds of Silurian age are present. As a thick section of Paleozoic beds is present in the northern part of the Providence Mountains, some beds of Silurian age probably occur there.

Devonian System. The Sultan limestone, which is 315 to 640 feet thick in the Goodsprings district, Nevada (Hewett, 1931), is separable into three members, the Ironside dolomite, Valentine limestone, and Crystal Pass limestone, on the basis of lithology. It has yielded numerous fossils which indicate the age as Devonian. Similar beds in the Nopah Range are about 895 feet thick, and are correlated with the Sultan limestone (Hazzard, 1938). Mapping in the hills south of the Mescal Range shows that the Sultan limestone continues southward as far as Kessler Peak, near Cima. It also is present in the Providence Mountains.

Hazzard (1938) noted an unconformity at the base of the Sultan limestone in the Nopah Range. An unconformity may be indicated by the sandy shale that yielded Devonian fossils near the top of the Goodsprings dolomite in the Goodsprings district.

Mississippian System. The Monte Cristo limestone, about 800 feet thick, is separable into five members on the basis of lithology in the Goodsprings district (Hewett, 1931). It also is present in the Nopah Range, Spring Mountains, and Providence Mountains. Almost everywhere, it contains abundant fossils which indicate the age as lower and middle Mississippian. On the north slope of the San Bernardino Mountains, the Furnace limestone, possibly about 4,500 feet thick, was first regarded by Vaughan (1922) as Upper Cambrian and Ordovician, but was later shown by Woodford and Harriss (1928) to be Mississippian. The age of the overlying Saragossa quartzite, first considered to be Silurian or Devonian, is therefore later Paleozoic.

Pennsylvanian System. In the Goodsprings District, Nevada, the Bird Spring formation, about 2,500 feet thick, was first considered to be wholly Pennsylvanian in age (Hewett, 1931), but later studies of the fauna from the adjacent area to the north by Longwell and Dunbar (1936) indicate that the upper 1,500 feet or more are probably Permian. In the Spring Mountains this formation is mainly limestone and dolomite with some sandstone and shale, and the base is an unconformity that can be recognized over a large area. Hazzard (1938) reports 780 feet of the Bird Spring formation in the Nopah Range, and a part of it probably is present in the Providence Mountains. James Richmond, who is engaged in stratigraphic studies in the San Bernardino Mountains south of Lucerne, recently reported (oral communication, 1953) the presence of fossils characteristic of the Bird Spring formation.

At several places in the Barstow quadrangle, Miller (1946) reports poorly preserved fossils from the Oro Grande series and from somewhat similar beds in the Paradise Range, 25 miles north of Barstow, that have been determined as Carboniferous, probably Mississippian. Bowen (1954) has determined the thickness of the Oro Grande series near Oro Grande to be about 9,670 feet, but this may include formations other than Carboniferous.

Permian System. Along the east slopes of the Spring Mountains, from Las Vegas on the north to Kokoweef Peak on the south, a distance of 60 miles, there are sporadic outcrops of a formation about 1,000 feet thick, composed of reddish sandstone with beds of gypsum. This is correlated with the Supai formation of northern Arizona (Hewett, 1931, 1954). The formation is not known south of Kokoweef Peak, nor west of the Spring Mountains.

The Kaibab limestone overlies the Supai formation and crops out widely along the east slopes of the Spring Mountains as far south as Clark Mountain. It is composed of two units of massive dolomite, each about 200 feet thick, separated by a layer of sandstone that generally is about 50 feet thick. This sandstone layer locally contains a thick bed of gypsum, which is mined near Arden, Nevada. The dolomite beds contain abundant fossils characteristic of the Kaibab limestone in the type locality in northern Arizona.

West and south of the Garlock fault, exposures of fossil-bearing Permian formations are sparse and widely separated. At the northwest corner of the Soda Mountains, west of Silver Lake, a plate of badly crushed limestone forms the west slope of a ridge for 3 miles. From this plate, Fusulinids reported to be Permian were collected by the writer in 1948. In mapping the 30-minute Barstow quadrangle during 1948-49, Bowen (1954) collected numerous fossils in the limestone pebbles of a conglomerate, 1,350 feet thick, that is a part of the Fairview Valley formation, about 6,000 feet thick. As determined by Merriam and Williams, most of the fossils indicate a Permian age for the pebbles; some of the other fossils are of other Upper Paleozoic ages. Bowen also found a few fossils in the matrix of the conglomerate, and their age also appears to be Permian. Curiously, fossil-bearing beds that could be the source of the pebbles are not known within 50 miles, although they could have come from Permian rocks now wholly eroded from the San Bernardino Mountains.

In the Saltdale quadrangle, Dibblee (1952) found lower or middle Permian Fusulinids in limestone that lies near the middle of the Garlock series, 23,000 feet thick. Doubtless other older Paleozoic and perhaps Mesozoic formations are present in the section, but no other fossils have been found.

Mesozoic Rocks

Triassic System. In the Spring Mountains and eastward as far as eastern Arizona, the basal Mesozoic unit is the Moenkopi formation. At the type locality, in northeastern Arizona, the formation is a continental assemblage of red shale and sandstone. Marine limestone appears in the formation in southwestern Utah and southern Nevada. Near Cottonwood Spring, 20 miles southwest of Las Vegas, the formation is a thin conglomerate overlain by 1,000 feet of fossil-bearing marine dolomite, the age of which is Lower Triassic (Hewett, 1931). The formation is known as far south as Kokoweef Peak (Hewett, 1954).

In recent geologic mapping in the northern part of the Soda Mountains, west of Silver Lake, Grose (1953) has found Lower Triassic gastropods that are characteristic of a zone in the Inyo Mountains. In mapping the Lane Mountain quadrangle, about 25 miles north of Barstow, McCulloh (1952) has found casts of pelecypods in highly altered sedimentary rocks; preliminary examination by S. W. Muller indicates that they may indicate an upper Jurassic or even Cretaceous age. If this is confirmed, some revisions of Mesozoic chronology will be required.

Sedimentary rocks near Goldstone, north of Barstow, and extrusive rocks in the Barstow quadrangle (Bowen, 1954) and the Ord Mountains (Gardner, 1941) are regarded as Mesozoic and probably Triassic on the basis of their lithology or their place in the stratigraphic section. In the central part of the Barstow quadrangle, the Sidewinder volcanic rocks, dacite flows and pyroclastics, are considered by Bowen (1954) to be Triassic. The Ord Mountains, 25 miles southeast of Barstow, consist mainly of highly altered andesite flows, tuffs, and breccias that are interpreted as Triassic by Gardner (1941).

In the Spring Mountains, the basal conglomerate beds of the Moenkopi formation are unconformable on the underlying Kaibab limestone.

Later Systems. The Shinarump conglomerate, Chinle formation, and Aztec sandstone are three sedimentary units that successively overlie the Moenkopi formation. With a total thickness of about 3,000 feet, they crop out almost continuously for about 50 miles along the east slope of the Spring Mountains (Hewett, 1954), and also appear in a small area near Kokoweef Peak. Nothing resembling them is known west of the Spring Mountains. On the basis of their stratigraphic position and lithology in northern Arizona and southern Utah, a Triassic age is assigned to the Shinarump conglomerate and Chinle formation, and a Jurassic age is assigned to the Aztec sandstone, which is considered to be the western equivalent of the Navajo sandstone (Hewett, 1931, 1954).

Intrusive Rocks. Much more is known about the kind and distribution of the intrusive rocks in the northeastern quarter and western half of the Mojave region than is known about those in the southwestern quarter. The data now available indicate that (1) late Mesozoic intrusive rocks occur widely over large areas in the entire Mojave region; (2) varieties of coarse-grained intrusive rocks that range from quartz monzonite to granite prevail in the northeast quarter; (3) a much wider range of varieties is found in the western half, including gabbro, quartz diorite, quartz monzonite, and granite; (4) where relations are clearly shown, the granite and quartz monzonite are definitely younger than the gabbro and quartz diorite; and (5) the age of the quartz monzonite at two localities, as determined from the lead-uranium ratios in minerals from contained pegmatites, is about 150 million years, which indicates intrusion in Middle Jurassic time.

In the Ivanpah quadrangle (Hewett, 1954) several varieties of quartz monzonite form at least one large and several small bodies, and granite forms several small bodies. The silica content of the quartz monzonites ranges from 67.0 to 71.5 percent, the potash from 4.31 to 5.91 percent, the soda from 3.10 to 4.17 percent, and the lime from 1.00 to 3.64 percent. The largest body of quartz monzonite intrudes a minor thrust fault that is a feature of the Laramide orogeny; the age appears to be post-Middle Cretaceous. No bodies of less silicic rock are known to have been intruded during this epoch of orogeny in the Ivanpah quadrangle.

In the Cady Mountains, 70 miles southwest of the largest body of quartz monzonite in the Ivanpah quadrangle, a large mass of similar quartz monzonite contains a pegmatite in which enough of the uranium-bearing mineral betafite was recovered to permit the determination of its age as about 155 million years (Hewett and Glass, 1953).

About 50 miles southwest of the Cady Mountains pegmatite, near Rock Corral in the eastern part of the San Bernardino Mountains, enough euxenite was recovered from a pegmatite in the Cactus granite (Woodford and Harriss, 1928) to permit the determination of its age as about 150 million years (Hewett and Glass, 1953). The age of two pegmatites in quartz monzonite in the central Mojave region is therefore Middle Jurassic.

According to Gardner (1941), the Upper Jurassic intrusive rocks of the Newberry, Ord, and northern Bristol Mountains include several varieties of quartz monzonite and granite; no more basic intrusive rocks have been noted. Bowen (1954) reports one large area of gabbro-diorite (Hodge complex) and several small bodies of quartz diorite, but bodies of younger quartz monzonite are much more widespread (Granite Mountains, north of Barstow).

In the Lane Mountain quadrangle, north of Barstow, McCulloh (1952) has mapped large bodies of quartz diorite and gabbro, into which quartz monzonite (Paradise Mountains) is intrusive. The youngest rocks intruded by the quartz diorite are Upper Triassic. The Granite Mountains, which lie north of the Paradise Mountains and are about 25 miles long, consist wholly of quartz monzonite of the type studied by the writer in the Ivanpah quadrangle (Hewett, 1954).

Recent geologic work by Dibblee (1954) in the western half of the Mojave region shows that quartz monzonite forms large bodies and locally intrudes smaller, less widespread bodies of hornblende diorite and hornblende quartz diorite. In the Randsburg district, the widespread Atolia quartz monzonite contains minor bodies of granite and diorite (Hulin, 1925). In the Neenach quadrangle, Wiese (1950) records large bodies of gabbro and diorite north of the Garlock fault, and large bodies of granite and quartz diorite south of that fault. In the Lebec quadrangle, west of the Neenach quadrangle, Crowell (1952) reports large bodies of quartz monzonite north of the Garlock fault and a large body of granite in the area between the Garlock and San Andreas faults; more basic intrusive rocks are sparse and form small bodies.

Late Mesozoic Orogeny. The Paleozoic and Mesozoic sedimentary rocks of the Mojave region are greatly deformed, and wherever they are in contact with the coarse intrusive rocks, it appears that the igneous rocks are related to the deformation. In a few places the age of the deformation is fairly clear, but in most occurrences the age must be inferred from what is known in nearby regions.

The area covered by the Ivanpah quadrangle (Hewett, 1954), as well as that covered by the Las Vegas quadrangle to the north, reveals that the Paleozoic and Mesozoic sedimentary rocks, of which the youngest are the Jurassic(?) Aztec sandstone and overlying flow breccia, are thrown into great open folds and broken by impressive thrust faults. From evidence near Overton, Nevada, where sedimentary rocks containing Middle Cretaceous fossil cycads are involved in thrust faults, it appears that the principal deformation is post-Middle Cretaceous, or within the period of Laramide orogeny (Longwell, 1949).

Faults and Folds in the Mojave Desert Region. The present state of knowledge concerning the faults of the Mojave Desert region is summarized elsewhere in this volume (Hewett, Contribution No. 2, Chapter IV). Within the Ivanpah quadrangle, five major and numerous minor thrust faults have been mapped (Hewett, 1954). Along the major faults, lower to middle Paleozoic formations rest upon lower to upper Mesozoic formations. Several of these faults extend from 15 to as much as 40 miles, and in general they trend north to northeast and dip westward at angles of 10° to 30°. The belt of thrusts has been traced from Las Vegas Wash on the north along the Spring Mountains as far south as Kelso Wash; none are known in the Providence Mountains, or south of them.

Even though only small areas have been studied and mapped along and north of the Garlock fault, it is known that, in the Nopah Range, in the Black, Funeral, and Panamint Mountains which border Death Valley, and in the Slate and Argus Ranges which border Searles Lake, the pre-Paleozoic and Paleozoic sedimentary formations maintain a northerly trend. In the El Paso Mountains (Hulin, 1925), the thick section (35,000 feet) of Paleozoic and Mesozoic(?) sedimentary rocks strikes about N. 30° W. and dips steeply northeast. Thus far, no major pre-Tertiary thrust faults are known from areas west of the Amargosa Valley.

Within the Mojave block, the same general northward trend of the beds seems to be maintained even though there are local departures, some of which seem to be caused by intrusive masses. Near Goldstone, north of Barstow, a section of clastic sediments and limestones, about 5,000 feet thick and probably of Mesozoic age, trends N. 20° W. and dips 30° east. On the north side of the Calico Mountains, a section of Paleozoic rocks, about 25,000 feet thick (McCulloh, 1952), strikes N. 10°-30° W. and dips uniformly east. An exception to this trend is found in the northern part of the Shadow Mountains, where Bennie W. Troxel (personal communication, 1953) recently has mapped a recumbent fold in upper Paleozoic(?) sedimentary rocks that trends S. 70° W. and is overturned northward. In the Barstow quadrangle (Bowen, 1954), the Hodge volcanic series, considered to be Paleozoic, trends east of north and dips steeply northwest. Near Oro Grande, the upper Paleozoic Oro Grande series appears to show a northward-plunging anticline; the Permian Fairview Valley formation trends west and dips steeply north.

Even though mapping is very incomplete, enough is known to indicate that, in the sparse patches of Paleozoic and Mesozoic formations within the Mojave block, the axes of folds generally follow those that are known in areas north and east of the Garlock fault; it is concluded that the deformation took place during the same period of orogeny, or from Middle Jurassic to Late Cretaceous time.

Until recently, the only basis for inferring the age of the Mesozoic orogeny shown within the Mojave block has been the relations to areas in and west of the Sierra Nevada. On this basis it has been considered "Jurassic." Determination of the ages of two uranium minerals from pegmatites in the Cady and San Bernardino Mountains now indicates that these bodies were intruded in Middle Jurassic time (Hewett and Glass, 1953).

It is not yet clear whether there were two distinct and separable Mesozoic orogenies in the Mojave region, one Middle Jurassic and the other post-Middle Cretaceous, or whether a wave of orogeny moved progressively eastward across the region, beginning in Middle Jurassic time in the west and culminating in Late Cretaceous time in the east.

Summary of Paleozoic and Mesozoic Sedimentary Rocks, Deformation, and Intrusive Rocks. The present state of geologic work in the pre-Tertiary rocks of the Mojave region permits some tentative conclusions. The thick sections of Paleozoic formations in the Nopah and nearby ranges indicates the existence of a major geosyncline or basin which was filled with a thick section of clastic sediments during Lower and Middle Cambrian time, but this basin did not extend east of the Spring Mountains. From Middle Cambrian time onward to the end of Paleozoic time, the basin received a thick section, largely of marine carbonate sediments.

From the Spring Mountains eastward, there was almost uninterrupted sedimentation into and through Mesozoic time, at least until Late Jurassic; this Mesozoic section continues with minor changes in lithology and thickness into and across the plateau region of northern Arizona. The marine beds of the Moenkopi formation of the Spring Mountains extend only into southwest Utah and northwestern Arizona; eastward, the beds are continental. What little is known of Mesozoic sediments in the region west of Death Valley indicates an abrupt change to quite different conditions of formation. The few patches of marine Triassic sedimentary rocks known in the Mojave block seem to belong to a different western province of deposition.

In reviewing the events of Cenozoic time in this region, it will be important to recall that thick sections of Paleozoic sedimentary rocks persisted southward into the Mojave block, even though only a few masses of such rocks remain and even though lower Paleozoic formations are not yet known. That there are now only remnants of thick Paleozoic and Mesozoic formations and no Tertiary formations older than middle Miocene within the Mojave block indicates that vigorous

			DEPOSITION	IGNEOUS	DEFORMATION	EROSION
QUATERNARY	RECENT		Lake Beds—Valley Wells	Basalt flows— cones Halloran Pisgah	Normal Faults— small	Erosion—internal drainage Erosion — internal drainage
	PLEISTOCENE	Late	Manix beds		Normal Faults— large Ivanpah Valley Local warping	
		Middle		Black Mtn. Basalt Halloran Basalt unconformity Andesite Red Mountain Dacite	— Warping	Erosion — internal drainage
			Resting Springs local, volcanic		Local warping	Great erosion—internal or external drainage Final stages—Ivanpah Upland
		Early				Great erosion — internal or external drainage Early stages — Ivanpah Upland
TERTIARY	PLIOCENE	Up.	none		Orogeny— profound {folds thrusts Amargosa Chaos Shadow Mtns. klippen	Great erosion—external drainage
		Mid	Lava Mtns. 5000 ± feet			
		Low	Ricardo 5000- Avawatz 8000 ft land waste volcanics 2 Basalt flows	2 Basalt flows	Broad warps local basins——filled with debris	Local—internal drainage
	MIOCENE	Up	Barstow 5000 ± feet Pickhandle Jackhammer			
		Mid			Broad warps	Local — internal drainage
		Low	Not Present			
	OLIGOCENE		Not Present (Titus Canyon — DEATH VALLEY)	none		Great erosion— external drainage
	EOCENE		Not Present (Goler beds — EL PASO RANGE)	none		Great erosion— external drainage

FIGURE 3. Tertiary-Quaternary episodes in the Mojave Desert region.

erosion took place from late Mesozoic into Middle Tertiary time. From this, the conclusion is reached that the Mojave block rose at least 15,000 feet, and perhaps 20,000 feet, during this interval, and that the rocks were removed as the block rose.

Hill and Dibblee (1950) recently have concluded, from the distribution and character of the Cretaceous sedimentary rocks, that movement on the San Andreas fault may have begun soon after these rocks were deposited. From what is stated above, it appears that the Garlock fault did not exist during the folding that accompanied the late Mesozoic orogeny, but that it had taken form by early Eocene time, when the Goler formation was laid down. During Eocene, Oligocene, and early Miocene time, the Mojave block stood above the surrounding regions to the north and south and underwent profound erosion.

Cenozoic Rocks

Tertiary Period. The nature, distribution, and age of the Tertiary sedimentary rocks in the Mojave block indicate that the history of sedimentation, volcanic activity, deformation, and erosion within this area differs in many ways from that of the region north of the Garlock fault and from that of the region south of the San Andreas fault. The absence of Eocene and Oligocene sedimentary rocks within the block, and their presence in nearby areas both north and south of it, indicate that the block stood above the surrounding areas and that it was subjected to erosion during these epochs. It seems probable, therefore, that movement on the Garlock fault began soon after the close of the late Mesozoic orogeny. By contrast, the evidence is growing that the San Andreas fault is older and may have taken form in pre-Cretaceous time (Hill and Dibblee, 1953).

The present state of knowledge of sedimentation, volcanism, deformation, and erosion in the Mojave region during Tertiary and Quaternary time is shown in figure 3. The chart is based largely upon information obtained by the writer during field work in the northeastern part of the region, especially in the Ivanpah quadrangle, and it should be considered most dependable for that area. An attempt has been made, however, to consider and use both published and much unpublished information for the other parts of the region. The recent field work of T. W. Dibblee, T. H. McCulloh, G. I. Smith, F. M. Byers, and D. H. Kupfer has been used by the writer, but the writer is responsible for some of the interpretations. The recent fossil collections of R. H. Tedford, R. L. Schultz, H. H. Winters, and K. E. Lohman have been invaluable. The identification of the Tertiary vertebrate collections is the work of G. E. Lewis of the U. S. Geological Survey.

The only Eocene sediments thus far known in the region are the basal beds of the Goler formation on the north slope of the El Paso Mountains (Hulin, 1925); the interpretation of age is based upon the identification of plants by Axelrod (1949). Dibblee (1952) considers that the Goler formation may include sediments of late Eocene, Oligocene, and possibly late Miocene age. Just south of the San Andreas fault on Rock Creek, 17 miles southeast of Palmdale, Dickerson (1914) made extensive collections of marine invertebrate fossils whose age is considered to be early Eocene (Martinez). Eocene sediments once may have extended northward from this area into the Mojave block, and since may have been eroded. The apparent absence of Eocene and Oligocene sediments from the Mojave block indicates that erosion was very active and that the products were removed from the area, probably outward to the southwest and to the southeast.

Miocene water-laid sediments are the most widespread of the Tertiary formations in the Mojave block. Abundant vertebrate fossil collections indicate that middle and upper Miocene sediments form thick sections in the Black Canyon area (Dibblee, 1954), the Barstow syncline (Dibblee, 1954), the Calico Mountains (McCulloh, 1952), and the Alvord Mountains (Byers, 1954). It is probable that parts of these basins or other basins extend northeast into upper Cronise Valley and southeast into Daggett basin, and possibly as far as Twentynine Palms. In the Calico Mountains, McCulloh (1952) has mapped two formations that underlie the Barstow formation unconformably. The lower of these, the Jackhammer formation, contains arkosic conglomerate and basalt flows, and the upper, the Pickhandle formation, consists of andesite and dacite flows and agglomerates. According to G. E. Lewis, the Barstow formation includes both middle and upper Miocene beds.

The only marine sediments of Miocene age thus far known within the Mojave block are small patches of the Santa Margarita formation mapped by Wiese (1950) several miles north of Quail Lake, east of Gorman.

In the Barstow syncline, as well as in the Black Canyon basin to the west and in the Calico basin to the east, the Barstow sediments contain a wide variety of materials, including coarse and fine waste from the bordering hills of pre-Tertiary rocks, as well as coarse and fine volcanic debris, pumice, tuffs, and, in a few places, local basalt flows. Gardner (1941) considered that the thick section of andesite flows and tuffs that form the Newberry Mountains is the equivalent of the Red Mountain andesite near Randsburg, but this seems improbable because they have been folded and faulted. These flows and tuffs, as well as those south of Troy, are probably middle or upper Miocene.

All of the areas within which vertebrate fossils indicate middle and late Miocene age show open folds, and locally even closed folds as in the crest of the Calico Mountains (McCulloh, 1952). In the absence of fossils, it seems that either middle or late Miocene or early or middle Pliocene age can be inferred if the beds show open or closed folds.

On the basis of abundant vertebrate fossils, Merriam (1914) applied the name "Ricardo" to a thick section of sediments on the northwestern slope of the El Paso Mountains, and interpreted them as early Pliocene in age. Recent work by Dibblee (1952) indicates that the section is about 7,000 feet thick, and is made up of coarse and fine waste from the nearby pre-Tertiary "basement" rocks, as well as volcanic debris and basalt flows. Similar sedimentary material is found several miles south of Red Rock Canyon on the south side of the Garlock fault, and may be of the same age.

In the vicinity of Castle Butte, east of Mojave, thin beds of limestone have yielded diatoms considered by K. E. Lohman to be lower Pliocene. Gale (1946), in studying the Kramer borate area farther east, interpreted several hundred feet of sediments that rest upon pre-Tertiary "basement" rocks as belonging to the Rosamond formation (upper Miocene), and regarded the overlying borate-bearing beds as the equivalent of the Ricardo formation. These interpretations were not based upon fossil material.

No sediments of Pliocene age have been recognized east of the Kramer area as far as the "Avawatz" beds, at the southeastern end of the Avawatz Mountains. These beds, made up largely of pumice and similar volcanic debris, have yielded abundant vertebrate material determined by Henshaw (1939) and G. E. Lewis as lower Pliocene. In the exposed area, the beds strike N. 70° W. and dip 30° northeast.

In the Shadow Mountains, 30 miles northeast of Baker (Hewett, 1954), there is a basin of Tertiary(?) sediments that consist largely of local land waste but in places contain much pumice and tuff; these beds have yielded fossil ostracods that are not diagnostic as to age. Within an area of about 5 by 8 miles, the Shadow Mountains contain 24 plates (klippe) of pre-Cambrian granite gneiss, which are remnants of an extensive thrust plate resting upon the inclined Tertiary sediments. The age of the Tertiary beds thus is very important.

Recent collecting by R. H. Tedford and R. L. Schultz and geologic mapping by G. I. Smith have shown that the sedimentary rocks that underlie the Red Mountain andesite (Hulin, 1925) and nearby Lava Mountains flows, and that were considered to be "Rosamond" by Hulin, actually should be regarded as lower middle Pliocene. The 5,000 feet of beds is largely land waste from the pre-Tertiary "basement," but also contains volcanic debris and lava flows. In the area are numerous folds with local dips as great as 70°, and there are many normal faults and some tear faults. The sedimentary basin seems to lie wholly south of the nearby Garlock fault. The sediments of this basin seem to be the youngest Tertiary beds now known in the entire Mojave Desert region.

With the possible exception of the El Paso Mountains, at no place in the Mojave region have fossil-bearing Pliocene sediments been shown to rest upon fossil-bearing Miocene sediments. Even in the extensive area of the central Mojave region that is underlain by Barstow sediments, no fossil-bearing Pliocene material has been found. This situation indicates that the down-warps were filled with middle and upper Miocene sediments and then became inactive, whereupon new down-warps, now filled with sediments of early Pliocene age, were formed. Subsequently, these younger down-warps ceased to be active, and new basins nearby were filled with lower middle Pliocene sediments.

Pliocene Orogeny. As noted above, the beds of Tertiary age, including the Goler formation (Eocene(?), Oligocene(?), Miocene (?)), the Barstow formation (middle and upper Miocene), the Ricardo formation and "Avawatz" beds (lower Pliocene), and the beds in the Lava Mountains (lower middle Pliocene), commonly show open folds with dips in the range of 20° to 40°. Dips of 60° and 70° are found locally.

Flat thrust faults, generally indicated by plates of old rocks (klippe) resting upon younger rocks, but in places by plates of young rocks resting upon older rocks, are known in the following areas:

1. Curry (1949) has made a geologic map of an area of about 140 square miles, in the Black Mountains on the east side of Death Valley, in the vicinity of Badwater, Copper Canyon, and Mormon Point. Within a belt about 25 miles long, several large and many small plates largely made up of Tertiary formations rest in discordance upon smooth surfaces of old rocks, mainly pre-Cambrian granite gneiss. Within the mapped area are three turtlebacks, which are plunging ridges whose smooth surfaces seem to coincide with the bases of the plates (see Curry, Contribution No. 7, Chapter IV). Many observers agree with Curry that these plates have been pushed over the older crystalline rocks, but there are differences of opinion concerning the origin of the "turtlebacks."

2. In the Virgin Spring area, which adjoins on the south the area mapped by Curry, Noble (1941) has mapped the "Amargosa Chaos" within an area of about 90 square miles. The "Amargosa Chaos" is a plate made up largely of old rocks, upper pre-Cambrian sedimentary rocks with some Tertiary rocks, that rests upon a smooth surface cut on lower pre-Cambrian crystalline rocks, largely gneiss. The "chaos" is separable into three phases or sheets on the basis

of the most abundant rock types present, and local evidence indicates that it was thrust over the old rocks from the east.

3. In the Tecopa area, about 20 miles east of the Virgin Spring area, Mason (1948) has mapped about 225 square miles, within which he has concluded that an extensive plate, composed of sections of upper pre-Cambrian and Lower Cambrian formations, has been thrust westward over lower pre-Cambrian gneiss.

4. In the Silurian Hills, about 25 miles south of the Tecopa area, Kupfer (1952) has mapped about 35 square miles within which a plate composed largely of upper Paleozoic sedimentary rocks has been thrust from the northeast over a base composed largely of upper pre-Cambrian sedimentary formations.

5. Within the Ivanpah quadrangle, which adjoins the eastern border of the Silurian Hills, Hewett (1954) has mapped thrust plates in four local areas. In the Kingston Range, the presence of two fensters of early pre-Cambrian gneiss, upon which large masses of upper pre-Cambrian and lower Paleozoic sedimentary formations rest in discordance, indicates that the Kingston Range mass has been thrust to its present position. Nearby on the south, in the Shadow Mountains, 24 blocks of lower pre-Cambrian gneiss with flat bases rest upon inclined beds of mid-Tertiary(?) sedimentary rocks; these blocks seem to be parts of a plate at least 5 by 8 miles in extent. East of the Shadow Mountains, near Winters Pass, and within an area about 5 miles in diameter, five klippen of lower Paleozoic sedimentary rocks rest in discordance upon a flat surface of lower pre-Cambrian gneiss; there are missing at the bases of the klippen about 5,000 feet of beds that are present 5 miles northeast.

6. In Old Dad Mountain, 40 miles south of the Shadow Mountains, a plate of Paleozoic sedimentary formations about 6 miles long rests in discordance upon a "basement" of pre-Cambrian rocks.

The six areas described briefly above seem to be parts of a belt that extends from Badwater in Death Valley southward to Old Dad Mountain, or for a distance of about 125 miles. This belt is 10 to 20 miles wide, and within it plates of rock—"chaos" in three areas and solid, unbrecciated masses in other areas—have been thrust to the positions that they now occupy. Several of the observers conclude that the plates have been thrust from the east, and one concludes that the plates he has studied have been thrust from the west. More work is needed before the direction of movement can be determined, but all the investigators agree that the plates of rock are exotic.

Klippen have been recorded from two other places in the Mojave region, but these are within the Mojave block. Noble (1934) reports a plate of pre-Cambrian quartz-mica schist with flat base that rests upon feebly-indurated gypsiferous shale, probably Tertiary in age, near Bitter Spring. Bowen (1954) records two small plates of steeply dipping Paleozoic dolomite that rest upon volcanic clays and gravel about 5 miles northwest of Barstow. The source of the isolated blocks of dolomite is not known.

In any attempt to determine the age of the one or more major deformations in the Mojave region, several considerations enter. In the region southwest of the San Andreas fault in southern California, the major Ventura and Los Angeles basins contain thick sections with a fairly complete record of each Tertiary epoch of sedimentation from Eocene to Pliocene. It is surprising, therefore, to find that, even though the Mojave block contains perhaps a dozen basins with Tertiary sedimentary rocks, (1) none of Eocene or Oligocene age are yet known; (2) some basins contain thick sections of middle and upper Miocene sediments, but none seem to contain superimposed Pliocene sediments; (3) several basins containing lower Pliocene sediments are known, but none show underlying Miocene sediments or overlying middle Pliocene sediments; and (4) the only middle (lower) Pliocene section is not underlain by older Pliocene or Miocene sediments.

This situation seems to indicate some shifting of areas of downwarp, with accompanying shifts in basins of deposition. It seems probable that the folds, and perhaps the local thrust faults now known to involve Tertiary sedimentary rocks, developed in late middle Pliocene time, after all of the sedimentary rocks were deposited.

Late Tertiary and Quaternary Faults. It has been stated earlier that the principal folds as well as the thrust faults of the late Mesozoic orogeny seem to trend north to northeast. The dominant trend of the basins that contain middle and upper Miocene sediments, however, is northwest. Within the Mojave block also, the known faults seem to be divisible into two groups: (1) those that strike northwest and have great linear extent, amounting to 20, 30, 40 or more miles (Helendale, Harper Valley, Blackwater), and (2) those that have diverse other strikes and do not seem to persist for great distances. Members of the first group are roughly parallel to the San Andreas fault, and are found largely in the southwest half of the Mojave block, south and southwest of Barstow. The other faults are found largely in the northeast half of the block, where they seem to be characteristic.

For most of the faults that trend northwest, it has not been possible thus far to determine the nature and amount of the displacement, nor the time when they took form. Recent movement has occurred along many of these faults, as indicated by displacements in playas, alluvial fans, recent lines of drainage, and by aligned faceted spurs. In contrast with the San Andreas and Garlock faults, where horizontal movement is demonstrable at many places, it has not yet been proved that such movement has taken place along more than a few of the northwest-trending faults, and even along these the movement is not great. The amount of dip-slip movement differs from place to place, and scissors movement has been proved on several of the faults.

None of the large northwest faults coincides with joint systems in intrusive rocks, nor with the foliation of laminated rocks. The features of this group of faults suggest that they were formed when the Mojave block was under great compression, possibly during early Tertiary time, when the block was rising. According to Bowen (1954) one of these faults north of Barstow shows reverse relations at one place and normal relations a few miles away. The evidence of recent normal movement on many of these faults indicates that relaxation of compressive stress took place within Quaternary time.

By contrast, the faults in the northeast half of the Mojave block have diverse strikes, are less extensive, and only a few show recent movement.

Late Pliocene and Early Pleistocene Erosion. Following the late middle Pliocene orogeny, the Mojave region was subjected to great erosion, sufficient to reduce the thrust plates east of the Death Valley trough to isolated blocks or klippen. It seems that during this period of erosion, the detrital material and other products were largely carried out of the region. The first record of sedimentation following the orogeny is the thin section of sediments now preserved as the Resting Springs formation, north of the Kingston Range (Hewett, 1954). Much of the eastern Mojave region seems to have been reduced to an upland surface, to which the name "Ivanpah upland" has been given east of the Silver Lake and Soda Lake troughs. Projecting above this surface, however, were impressive mountains such as Clark Mountain and the Mescal Range. These mountains are made up of carbonate rocks, whereas the upland surface was perfected on igneous and metamorphic rocks.

The next episode, well recorded in the western part of the Mojave region, seems to have been the extrusion of the Red Mountain andesite in the Randsburg quadrangle (Hulin, 1925). The flat base of the andesite rests upon a surface of erosion cut across folded sediments that are known to be lower middle Pliocene in age. Latite flows in the Lane Mountain quadrangle (McCulloh, 1952) and dacite flows east of Superior Valley and near Camp Irwin are here regarded as the local equivalents of the Red Mountain andesite. Remnants of similar flows are found near Yermo. The area within which these remnants of flows occur also contains plugs of similar rocks.

Black Mountain Basalt Flows. The basalt flows that cap Black Mountain, 25 miles northwest of Barstow, rest upon a horizontal surface eroded on folded Barstow beds; no horizontal sediments have been found under the basalt flows, but near Camp Irwin there is a 100-foot sheet of sediments under what seems to be the Black Mountain basalt. West of Camp Irwin, this basalt flow locally rests upon an eroded dacite flow (Red Mountain andesite). The extensive basalt flows that lie upon the Ivanpah upland between Halloran Spring (U. S. Highway 91) and Valley Wells probably covered more than 250 square miles. At present the remnants of the flows reveal a broad anticline with 1,500 feet of relief. This fold extends southeastward to the area west of Cima Dome.

In the type area, the Black Mountain basalt flows are essentially horizontal on the mountain, but dip abruptly southward at the south face, where they are broken by the Harper Valley fault, one of the extensive northwest-trending faults of this area. Similarly, the great normal faults that limit Ivanpah Valley are younger than the Ivanpah upland, and probably are younger than the basalt flows that rest upon it. Even though there is some hazard in assuming contemporaneity of surface flows of similar rocks, this assumption is made for the present; at least several of the great normal faults of the Mojave region seem to show movement that is younger than these basalt flows.

Late Pleistocene Erosion. North of the Garlock fault are the long southward-trending valleys that include Owens, Searles, Panamint, and Death Valleys; all except Searles Valley show impressive normal faults along their borders, but most geologists who have examined them seem to agree that they are due in part to erosion. Noble (1941) considers that warping has played a part in the formation of Death Valley.

What was the course of the streams that flowed in these valleys, and what became of the products of erosion? Did they flow south into and across the Mojave block, and thence southeastward and possibly southwestward to the sea? To the writer, it seems probable that before the waters of Owens River entered and successively filled Owens Lake, China Lake, Searles Lake, Panamint Lake, and finally Death Valley, they entered the Leach trough, the major valley that follows the Garlock fault, and thence joined the Death Valley trough north of the Avawatz Mountains. From this point they probably flowed southward through Silver Lake, Soda Lake, and Bristol Lake to join the Colorado River estuary. Evidence is accumulating that the valleys of Owens Lake, Searles Lake, and Panamint Lake did not continue southeastward across the Mojave block.

Recent work in the Mojave block seems to indicate that during at least a part of Pleistocene time, there were several integrated drainage systems that discharged southeastward into the Colorado River estuary; their heads seem to have lain in the western half of the

Mojave block. An ancestral Mojave River probably rose in the San Gabriel Mountains. Recent studies of ground-water and the depth of alluvium in some of the basins of the central and western Mojave block seem to confirm this concept. Work in several parts of the region also indicates that some of the present playas have been formed by recent faults that interrupt the integrated drainages. Examples include Mesquite Lake near Twentynine Palms, and probably Dale Dry Lake.

The record of Tertiary sedimentation in the Mojave region, especially in the Mojave block, shows that this block rose 15,000 feet or more during Eocene and Oligocene time, and that erosion almost kept pace with the uplift. It also seems likely that the Mojave block developed integrated drainage systems during Middle and Late Tertiary time, largely internal during Miocene and early and middle Pliocene time, and possibly external during a part of late Tertiary and early Pleistocene time. Without much doubt, drainage in the western two-thirds of the Mojave region has been internal during late Pleistocene and Recent time.

The Manix lake beds, along the lower Mojave River, are the best record of Pleistocene sedimentation in the Mojave region (Buwalda, 1914). Studies of vertebrate fossils by Merriam have indicated that the beds are early Pleistocene in age. Recent work and collecting by Winters (1953) indicate that some of the vertebrates are early Pleistocene but that others are definitely late Pleistocene in age. According to Howard (1954), the eleven varieties of birds recently found are late Pleistocene in age.

It appears to the writer that the part of the valley of the Mojave River east of Troy Lake, within which the Manix lake beds were deposited, is much younger than an older valley that drained southeast from Troy Lake to Ludlow, Bristol Dry Lake, and the Colorado River valley. Another similar old valley extended southeast from the Ord Mountains to the Colorado River valley, but it is now fragmented by several faults, the Mesquite fault in Mesquite Dry Lake near Twentynine Palms and the fault that limits the Sheep Hole Mountains, north of Dale Dry Lake. It seems likely that fragmentation of the principal drainages in the eastern part of the Mojave region preceded the deposition of the Manix lake beds.

Hubbs and Miller (1949) conclude from the study of isolated (relict) living species of fish that the Death Valley trough drained southeast to the Colorado River through part of Quaternary time.

Recent Basalt Flows. Cinder cones are found widely in the Mojave region, and many flows of basalt have moved down Recent valleys. In the southwestern quarter of the Ivanpah quadrangle, surmounting the field of basalt flows described above, there are 26 cinder cones and related flows that are confined to the present valleys (Hewett, 1954). A single cone surmounts an extensive flow in the Newberry Mountains (Gardner, 1941). Mt. Pisgah is a cinder cone that rests upon an extensive flow between Hector and Lavic; others lie at Dish Hill, several miles east and southwest of Amboy.

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2. GEOLOGY OF THE IMPERIAL VALLEY REGION, CALIFORNIA

BY T. W. DIBBLEE, JR.*

This report is a geologic summary of detailed field work done by the writer in 1943 and 1944 under the direction of Rollin W. Eckis and Harold W. Hoots. Eckis had mapped an area in the southeastern Santa Rosa Mountains and Clark Valley as a thesis problem in 1931. The writer is indebted to Richfield Oil Corporation for permission to publish this report, to Rollin W. Eckis and to Mason L. Hill for criticism of the manuscript, and to Joseph Ernst of the Texas Company for information and discussion.

The Imperial-Coachella Valley is a broad, flat, alluviated area that lies partly below sea level. It is cut off from the Gulf of California to the south by the Colorado River delta. The lowest part of the valley is flooded by the Salton Sea, an inland lake 240 feet below sea level that serves as the sump for all drainage within the mapped region.

For purposes of the following geologic discussions, the Imperial Valley region can be divided into three general areas. These are: (1) northeastern Coachella Valley, including the Indio and Mecca Hills, and Durmid Hill northeast of Salton Sea; (2) northwestern Imperial Valley, including the Superstition Hills, San Felipe Hills west of Salton Sea, rising northwestward to the Santa Rosa Mountains, Borrego Mountain and Badlands, and Borrego and Clark Valleys; and (3) southwestern Imperial Valley, including the Yuha desert area, Coyote Wells Valley, Coyote Mountains, Carrizo-Vallecito Valley, and Fish Creek-Vallecito Granite Mountains.

STRATIGRAPHY

Pre-Tertiary Rocks

The Chuckwalla complex, named by Miller (1944) from the Little San Bernardino and Cottonwood Mountains, is of supposed pre-Cambrian age, and is composed of gneiss intricately intruded by hornblende diorite and leuco-granitic rocks.

The Orocopia schist, named by Miller (1944), is a dark gray mica schist of supposed pre-Cambrian age. Many thousands of feet of this rock are exposed in the Orocopia Mountains, and the schist extends westward under the Tertiary sediments of the Mecca Hills.

Unnamed metasediments of Paleozoic (?) age, composed of dark-colored biotite schist and interbedded white limestone, crop out in the Santa Rosa Mountains where a thickness of possibly 20,000 feet is exposed. The series is metamorphosed to gneiss and marble where it lies within or adjacent to granitic intrusive rocks.

In the Carrizo Peak area of the Coyote Mountains is exposed about 10,000 feet of gray mica schist and gray to white limestone of Paleozoic (?) or Triassic (?) age. Southward and westward from Carrizo Peak this series is increasingly metamorphosed to gneissoid granitic rocks at the southeast and west ends of the Coyote Mountains. The schist appears to have been granitized in place, and the limestone lentils have been recrystallized to marble.

In parts of the Fish Creek Mountains, and in the foothills of the Peninsular Ranges southwest and south of Coyote Wells, is a series of gneisses, gneissoid granites, and scattered lentils of marble. These rocks probably are the same as the schist-limestone series of the Coyote Mountains, but represent a more highly advanced stage of metamorphism.

Hornblende-rich diorite, with facies of quartz diorite and gabbro, are the dominant intrusive rocks of the low mountains within the Imperial Valley region, such as Signal Mountain, Superstition Mountain, Fish Creek-Vallecito Mountains, Borrego Mountain, and the eastern foothills of the Santa Rosa Mountains.

Granodiorite and subordinate granite, quartz monzonite, and quartz diorite are the dominant rock types of the Peninsular Ranges, where they form parts of the southern California batholith of probable Cretaceous age (see Larsen, Contribution 3, Chapter VII). These rock types extend northward through Granite Mountain, the mountains west of Borrego Valley, and into the San Jacinto Mountains. From the San Jacinto Mountains sill-like wedges of the granitic rocks extend southeastward into the metasediments of the Santa Rosa Mountains. The granitic rock types appear to intrude both the metamorphic and dioritic rocks to the east, and evidently crystallized from great masses of acidic magmas.

Granite pegmatite occurs as numerous subparallel dikes in the igneous and metamorphic rocks in the Peninsular Ranges and in Granite Mountain, and extend as far east as the Coyote and Fish Creek Mountains. Pegmatites of intermediate to basic composition are present, as well (see Jahns, Contribution 5, Chapter VII).

Cenozoic Rocks

The irregular surface of erosion developed on the crystalline rocks is overlain by a great thickness of Cenozoic clastic sediments that fill the Imperial depression and were derived from the adjacent mountain areas and from the drainage area of the Colorado River. The series represents essentially continuous deposition since Miocene time, and attains a maximum exposed thickness of 16,500 feet in

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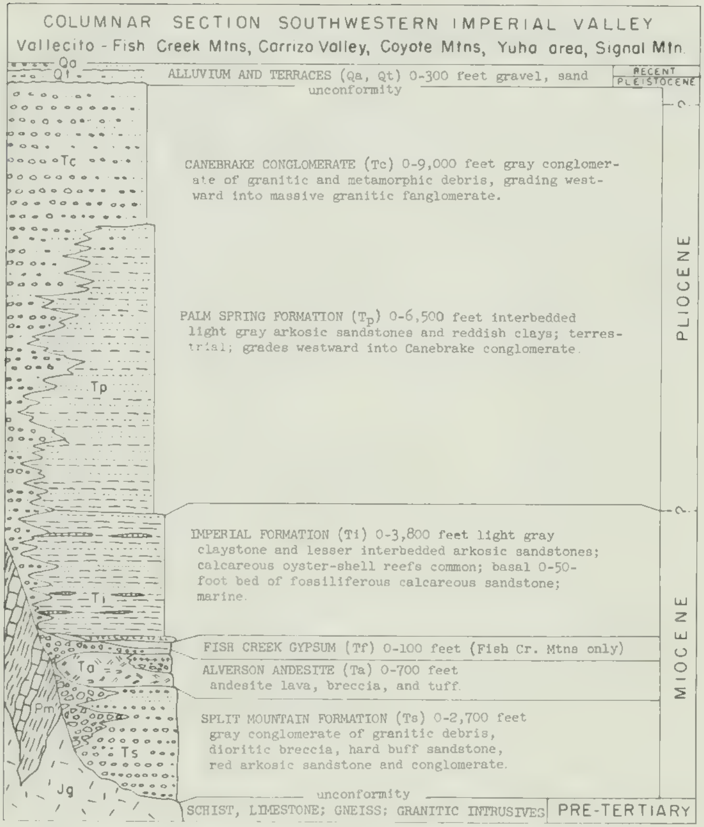
COLUMNAR SECTION SOUTHWESTERN IMPERIAL VALLEY
Vallecito - Fish Creek Mtns, Carrizo Valley, Coyote Mtns, Yuha area, Signal Mtn.
Qa
Qt
ALLUVIUM AND TERRACES (Qa, Qt) 0-300 feet gravel, sand
unconformity
RECENT
PLEISTOCENE
Tc
CANEBRAKE CONGLOMERATE (Tc) 0-9,000 feet gray conglomerate of granitic and metamorphic debris, grading westward into massive granitic fanglomerate.
PLIOCENE
Tp
PALM SPRING FORMATION (Tp) 0-6,500 feet interbedded light gray arkosic sandstones and reddish clays; terrestrial; grades westward into Canebrake conglomerate.
?
Ti
IMPERIAL FORMATION (Ti) 0-3,800 feet light gray claystone and lesser interbedded arkosic sandstones; calcareous oyster-shell reefs common; basal 0-50-foot bed of fossiliferous calcareous sandstone; marine.
MIOCENE
FISH CREEK GYPSUM (Tf) 0-100 feet (Fish Cr. Mtns only)
Ta
ALVERSON ANDESITE (Ta) 0-700 feet andesite lava, breccia, and tuff.
Pm
Ts
SPLIT MOUNTAIN FORMATION (Ts) 0-2,700 feet gray conglomerate of granitic debris, dioritic breccia, hard buff sandstone, red arkosic sandstone and conglomerate.
Jg
unconformity
SCHIST, LIMESTONE; GNEISS; GRANITIC INTRUSIVES
PRE-TERTIARY

FIGURE 1. Columnar section for southwestern Imperial Valley.

southwestern Imperial Valley, 18,700 feet in northwestern Imperial Valley, and 8,600 feet in northeastern Coachella Valley. Seismic data suggest that the sedimentary fill is more than 20,000 feet thick in Imperial and Coachella Valleys. The Cenozoic sediments accumulated in a trough that connected with the Gulf of California, but not with any of the California coastal basins.

Cenozoic Stratigraphy of Southwestern Imperial Valley. The Split Mountain formation, named by Tarbet (1944), is essentially a coarse basal conglomerate of Miocene age that is present only locally on an irregular surface cut on the older crystalline rocks. It is conformably overlain by younger formations. At the type locality in Split Mountain Gorge, south of Ocotillo, the formation is about 2,700 feet thick and is composed of basal red and gray granitic fanglomerate, sandstone, and dioritic breccia at the top. The formation thins out southeastward, and is present in the Coyote Mountains at only two localities. It is widespread south of Coyote Wells Valley, where it appears as granitic fanglomerate.

The Alverson andesite lava is a dark brown basic andesite of probable upper Miocene age that overlies the Split Mountain conglomerate and the older "basement" rocks in the western foothills of Coyote Wells Valley, in the Coyote Mountains, and in the Fish Creek Mountains. The lava is about 400 feet thick at Alverson Canyon, the type locality, and about 700 feet thick at the east end of the Coyote Mountains, where it is associated with tuff and breccia.

The Fish Creek gypsum is a playa deposit of white, bedded gypsum and anhydrite that rests on the Split Mountain conglomerate and is overlain by the Imperial formation in the western Fish Creek Mountains. It ranges in thickness from a knife edge to about 100 feet. A part of this extensive deposit is being quarried by the United States Gypsum Company (Ver Planck, 1952). The most northwesterly exposure contains celestite at the top (Durrell, 1953).

The Imperial formation, named by Woodring (1931), is a series of marine clays and sandstones that lie with essential concordance on the Alverson lava, the Split Mountain formation and the Fish Creek gypsum, or in some areas, unconformably on the "basement" rocks. They grade upward into the Palm Spring formation. The Imperial beds are extensively exposed from the Fish Creek Mountains southeastward to the northwest foothills of Signal Mountain, across the Mexican border. The section is composed of gray, yellow-weathering claystone; interbedded buff sandstone and dark, calcareous, oyster-shell reefs; and a basal calcareous or sandy bed that contains numerous mollusks and some corals. The claystone contains Foraminifera, ostracods, and diatoms. The fauna of the Imperial formation is of the shallow marine gulf type, and indicates an upper Miocene or possibly a lower Pliocene age (see Durham, Contribution 4, Chapter III).

At the type area on the south side of Carrizo Valley, the Imperial formation is about 2,500 feet thick, and it thins out westward. On the north side of the valley at Fish Creek Wash, it is about 3,700 feet thick. On the east and south sides of the Coyote Mountains, the formation is about 2,700 feet thick, and it lenses out west of Coyote Wells. At Yuha Buttes the uppermost 1,000 feet of the Imperial formation is exposed, and west of Signal Mountain the formation is 500 feet to 1,500 feet thick.

The Palm Spring formation, named by Woodring (1931), is a thick series of land-laid arkosic sandstones and red clays of Pliocene age. It grades downward into the marine Imperial formation, upward and westward into the Canebrake conglomerate, and is exposed extensively from Carrizo Valley southeastward to Signal Mountain. The Palm Spring formation was deposited throughout the Imperial depression after marine waters of the Gulf were barred from it, probably by the damming action of the Colorado River delta. Fragments of silicified wood, chiefly ironwood, are common throughout the formation.

The Palm Spring formation is about 4,800 feet thick at the type locality, on the south side of Carrizo Valley, and it thins westward. On the north side of Carrizo Valley it thickens to about 6,500 feet at Fish Creek Wash, thence eventually grades westward into the Canebrake conglomerate.

The Canebrake conglomerate, named after Canebrake Wash, is the coarse marginal conglomerate facies of the Palm Spring and Imperial formations. The type section is at the southeastern base of Vallecito Mountain, 3 miles west of Fish Creek Wash, where the conglomerate is about 7,000 feet thick. The most westerly exposures are fanglomerate that laps onto and against the crystalline "basement" rocks. Southeastward along the strike, the lower 4,000 feet of the conglomerate grades into the Imperial and Palm Spring formations, and the upper 3,700 feet persists basinward into Carrizo Valley as a gray pebble and cobble conglomerate that rests on the Palm Spring formation. This conglomerate thins to about 2,500 feet on the south side of Carrizo Valley, and to 2,000 feet on the south side of the Coyote Mountains.

Cenozoic Stratigraphy of Northwestern Imperial Valley. Conglomerate and sandstone of the Split Mountain formation crop out only at a very small exposure on the north flank of Superstition Mountain, where they are about 200 feet thick. In the San Felipe Hills this formation was encountered beneath the Imperial formation in three deep wells. On the peak southeast of the Santa Rosa Mountains, it may be represented by diorite-rich breccia.

The Imperial formation is partially exposed in the San Felipe Hills, and was penetrated in that area by three deep wells in which a total thickness of about 3,600 feet is indicated. In the isolated low hills north of Ocotillo, the basal part of the Imperial formation is exposed immediately above a biotite schist. Westward and northwestward the Imperial formation laps out against "basement" rocks. It is not present in Borrego Mountain nor in the Santa Rosa Mountains, except for about 50 feet of fossiliferous sandstone a mile southwest of Travertine Point near Salton Sea.

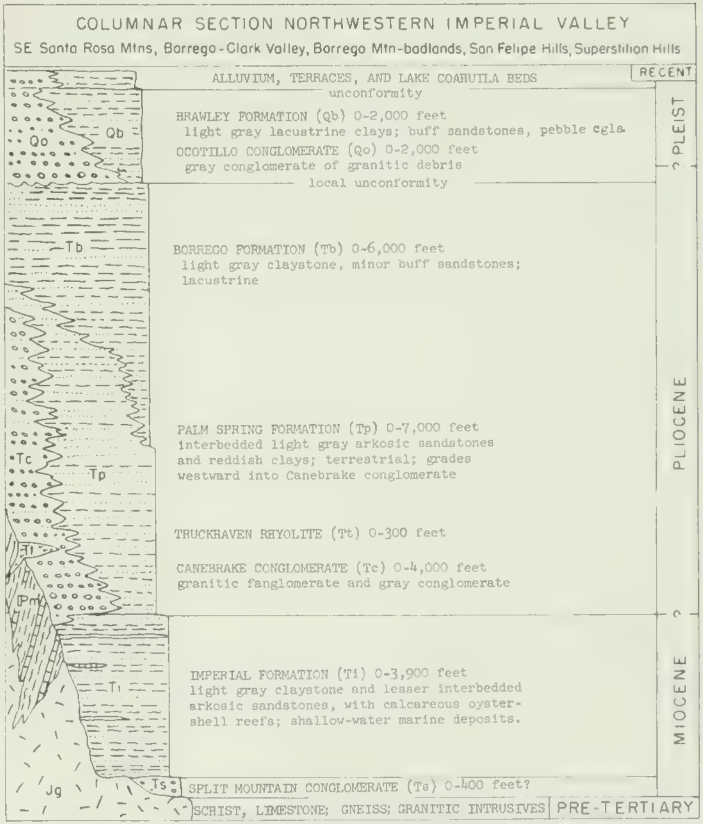
COLUMNAR SECTION NORTHWESTERN IMPERIAL VALLEY
SE Santa Rosa Mtns, Borrego-Clark Valley, Borrego Mtn-badlands, San Felipe Hills, Superstition Hills
ALLUVIUM, TERRACES, AND LAKE COAHUILA BEDS
RECENT
unconformity
BRAWLEY FORMATION (Qb) 0-2,000 feet
light gray lacustrine clays; buff sandstones, pebble cgls.
OCOTILLO CONGLOMERATE (Qo) 0-2,000 feet
gray conglomerate of granitic debris
local unconformity
PLEIST
?
Qb
Qo
Tb
BORREGO FORMATION (Tb) 0-6,000 feet
light gray claystone, minor buff sandstones; lacustrine
PALM SPRING FORMATION (Tp) 0-7,000 feet
interbedded light gray arkosic sandstones and reddish clays; terrestrial; grades westward into Canebrake conglomerate
Tc
Tp
PLIOCENE
TRUCKHAVEN RHYOLITE (Tt) 0-300 feet
Tt
CANEBRAKE CONGLOMERATE (Tc) 0-4,000 feet
granitic fanglomerate and gray conglomerate
Pm
?
IMPERIAL FORMATION (Ti) 0-3,900 feet
light gray claystone and lesser interbedded arkosic sandstones, with calcareous oyster-shell reefs; shallow-water marine deposits.
Ti
MIOCENE
Jg
Ts
SPLIT MOUNTAIN CONGLOMERATE (Ts) 0-400 feet?
SCHIST, LIMESTONE; GNEISS; GRANITIC INTRUSIVES
PRE-TERTIARY

FIGURE 2. Columnar section for northwestern Imperial Valley.

The Palm Spring formation is extensively exposed throughout the San Felipe Hills and westward into Borrego Valley, where it grades downward into the Imperial marine beds and upward into the Borrego lacustrine beds. The formation attains its maximum thickness of 7,100 feet in the Borrego Badlands. It thins eastward to 6,800 feet on the north flank of the San Felipe Hills anticlinorium, and to 3,600 feet or less on the east-plunging nose and the south flank of this structural feature.

The Canebrake conglomerate is the coarse marginal facies of the Palm Spring formation, as in the Carrizo Valley area. At the southeast end of the Santa Rosa Mountains, the entire thickness of the Palm Spring red beds that are exposed west of Salton Sea grades laterally westward into granitic conglomerate of the Canebrake facies, which rests on crystalline rocks and extends far up the slopes of the Santa Rosa Mountains as fanglomerate. In Borrego Mountain the lower part of the Palm Spring formation is represented by the Canebrake conglomerate facies.

The Truckhaven rhyolite crops out near Truckhaven, west of Salton Sea, where the lava forms a lens of varicolored felsitic rock that was extruded along an adjacent east-west fault. The lens is 100 feet in maximum thickness, and wedges out southward into the Canebrake conglomerate.

The Borrego formation, named by Tarbet (1944), is of probable upper Pliocene age. It has been mapped by the writer as the lacustrine facies of the terrestrial Palm Spring formation, and is composed of light gray claystone and interbedded sandstone. The claystone contains a lacustrine fauna of minute mollusks, ostracods, and rare Foraminifera. Fragments of petrified wood are rare. In the Borrego Badlands, the type section, the Borrego lake beds grade downward into terrestrial beds of the Palm Spring facies, and are overlain by the Ocotillo conglomerate.

The Borrego formation attains its maximum thickness of about 6,000 feet in the Borrego Badlands, and thins westward to only 2,000 feet at the west edge of this area. It thins eastward to 2,900 feet on the north flank of the San Felipe anticlinorium, to 2,000 feet on the east plunge of that feature, and on the south flank of the anticlinorium it is overlapped by the Ocotillo conglomerate.

The Ocotillo conglomerate overlies the Borrego lacustrine clays, and, together with the Brawley lake bed facies into which the conglomerate grades, forms the youngest unit of the Cenozoic series in Imperial Valley. It is either upper Pliocene or lower Pleistocene in age. The type section is in the northern part of the Borrego Badlands northeast of Borrego, where the formation is composed of about 800 feet of gray granitic-pebble conglomerate that lies conformably upon the Borrego clays. The Ocotillo conglomerate, as exposed near Ocotillo and eastward on the south flank of the San Felipe Hills anticlinorium, is about 1,000 feet thick and lies unconformably upon the Borrego clays. Northeastward from Ocotillo, it overlaps onto the Palm Spring and Imperial formations. Eastward in the San Felipe Hills, the conglomerate grades laterally and basinward into the Brawley lacustrine beds.

The Brawley formation is the lacustrine and continental basinward facies of the Ocotillo conglomerate, and is lithologically very similar to the underlying Borrego lake beds. The type section of this formation is just west of U. S. Highway 99 and west of the south end of Salton Sea, where about 2,000 feet of light gray claystone and thin interbeds of buff sandstone is exposed. The clays contain a minute lacustrine fauna like that of the underlying Borrego clays.

In the Superstition Hills the Brawley formation is composed of lacustrine and terrestrial clays, sands, and pebble gravels, and the base is not exposed. Around Superstition Mountain the Brawley formation, the basal portion of which is the Ocotillo conglomerate facies, unconformably overlaps the Imperial formation, Alverson lava, and the Split Mountain formation onto diorite. Southeastward and adjacent to the Superstition Mountain fault, the Ocotillo-Brawley series lies unconformably on the Borrego clays, and an angular discordance of as much as 60° is exposed north of the fault.

Cenozoic Stratigraphy of Northeastern Coachella Valley. The Dos Palmas rhyolite crops out in the Mecca Hills, 8 miles S. 30° E. of Mecca, and is of probable Miocene age. It rests directly upon much older crystalline rocks.

The Mecca formation is essentially a basal conglomerate of granitic and metamorphic debris that lies upon the ''basement'' rocks and is overlain by the Palm Spring formation in the Mecca and Indio Hills. It correlates with either the Split Mountain formation or the basal Canebrake conglomerate. The type section of the Mecca conglomerate is on the Mecca Hills anticline at Painted Canyon, 5 miles northeast of Mecca, where the conglomerate is about 400 feet thick. Two miles northwest of Painted Canyon, the upper part of the formation contains reddish sands and clays, and in another exposure a mile farther north, the conglomerate contains cobbles of sandstone with marine Eocene fossils. On the Mecca Hills anticline, 3 miles southeast of Painted Canyon, the Palm Spring formation is unconformably underlain by about 600 feet of the Mecca formation, which here consists of hard, pinkish gray sandstones and reddish clays. The base is not exposed.

The Imperial formation crops out only in the northwestern Indio Hills, where only the uppermost part of the fossiliferous, yellow-weathering clays is exposed beneath the Palm Spring and Ocotillo formations. On the south side of a low hill near Garnet, 12 miles northwest of Edom, 50 feet of fossiliferous sandstone questionably assigned to the Imperial formation lies unconformably beneath the Ocotillo conglomerate.

The Palm Spring formation crops out in both the Indio and Mecca Hills, where it consists of superbly exposed red to buff arkosic sandstones and thin interbeds of reddish to greenish clays. In the northwestern Indio Hills the formation is about 2,000 feet thick and overlies the Imperial marine clays, and in the southeastern Indio Hills it is about 3,300 feet thick and overlies the Mecca conglomerate. In the Mecca Hills east of the San Andreas fault, the Palm Spring formation is about 4,800 feet thick, lies above the Mecca formation, and grades eastward into the Canebrake conglomerate facies. West of the fault only the uppermost 1,500 feet of the Palm Spring for-

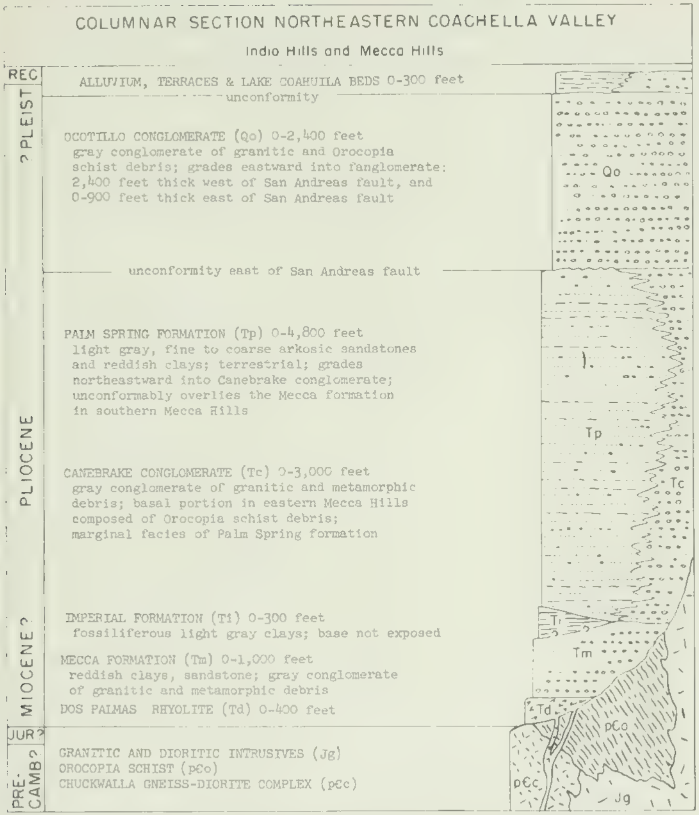
COLUMNAR SECTION NORTHEASTERN COACHELLA VALLEY
Indio Hills and Mecca Hills
REC
ALLUVIUM, TERRACES & LAKE COAHUILA BEDS 0-300 feet
unconformity
? PLEIST
OCOTILLO CONGLOMERATE (Qo) 0-2,400 feet
gray conglomerate of granitic and Orocopia schist debris; grades eastward into fanglomerate; 2,400 feet thick west of San Andreas fault, and 0-900 feet thick east of San Andreas fault
Qo
unconformity east of San Andreas fault
PLIOCENE
PALM SPRING FORMATION (Tp) 0-4,800 feet
light gray, fine to coarse arkosic sandstones and reddish clays; terrestrial; grades northeastward into Canebrake conglomerate; unconformably overlies the Mecca formation in southern Mecca Hills
Tp
CANEBRAKE CONGLOMERATE (Tc) 0-3,000 feet
gray conglomerate of granitic and metamorphic debris; basal portion in eastern Mecca Hills composed of Orocopia schist debris; marginal facies of Palm Spring formation
Tc
MIOCENE?
IMPERIAL FORMATION (Ti) 0-300 feet
fossiliferous light gray clays; base not exposed
Ti
MECCA FORMATION (Tm) 0-1,000 feet
reddish clays, sandstone; gray conglomerate of granitic and metamorphic debris
Tm
DOS PALMAS RHYOLITE (Td) 0-400 feet
Td
JUR?
PRE-CAMB?
GRANITIC AND DIORITIC INTRUSIVES (Jg)
OROCOPIA SCHIST (p€o)
CHUCKWALLA GNEISS-DIORITE COMPLEX (p€c)
p€o
p€c
Jg

FIGURE 3. Columnar section for northeastern Coachella Valley.

mation is exposed. Here it consists of red clays and white arkosic sandstones. Near Durmid, east of the fault, the uppermost 1,500 feet of the Palm Spring formation is exposed, and consists of hard, pinkish gray sandstone.

The Canebrake conglomerate facies of the Palm Spring formation is partly exposed in the southeastern Indio Hills, where the sandstones of the Palm Spring formation grade northward into it. The conglomerate is difficult to distinguish from the overlying Ocotillo conglomerate. In the eastern Mecca Hills, the Palm Spring sandstones grade eastward into the Canebrake conglomerate, which is composed of granitic and metamorphic debris. This conglomerate laps onto the Orocopia schist. Southeast of Box Canyon the basal part of the Canebrake conglomerate rests upon the Dos Palmas rhyolite, and is composed entirely of Orocopia schist debris.

The Ocotillo conglomerate crops out extensively in both the Mecca and Indio Hills. It is of the same facies and probably is of the same age as the Ocotillo conglomerate west of Salton Sea. It is the youngest formation of the Cenozoic series exposed in the hills northeast of Coachella Valley, and probably is of upper Pliocene or lower Pleistocene age. The conglomerate is a piedmont alluvial fan deposit of granitic and metamorphic debris derived from the mountains to the northeast. The top is a surface of deposition, which is undisturbed at the foot of the mountains but which becomes increasingly deformed and eroded as traced westward in the Mecca and Indio Hills. In the Mecca Hills east of the San Andreas fault, the conglomerate ranges in thickness from a knife edge to 900 feet, and lies unconformably on older formations. West of the fault it is about 2,500 feet thick and overlies the Palm Spring red beds. On both sides of the fault the conglomerate contains a large percentage of Orocopia schist debris. In the Indio Hills the Ocotillo conglomerate is about 2,100 feet thick. It lies unconformably on the Canebrake, Palm Spring, and Imperial formations, and shows a northwestward overlap.

In the Durmid area, northeast of Salton Sea, about 6,100 feet of lacustrine beds of the Borrego-Brawley facies is upended and contorted on the southwest side of the San Andreas fault. Near Bertram the lowest 1,200 feet of these beds is composed of hard, buff sandstones and interbeds of gray claystone; it may be equivalent to the Palm Spring formation but appears to be of lacustrine origin. These beds are overlain by about 2,700 feet of light-gray, thin-bedded claystones that contain thin sandy beds and many layers, as much as five feet thick, of white salines, chiefly sodium sulfate (Sampson and Tucker, 1942). This last-named section probably correlates with the type Borrego formation. The beds are overlain by about 2,200 feet of light gray claystone with a small amount of sandstone, which are exposed along the shore of Salton Sea. They are similar to, and may correlate with, the type Brawley lacustrine beds. No superjacent formation is present in this area.

Stratigraphy of Imperial Valley Proper. In recent years several deep wells were drilled for oil in the flat, alluviated portion of Imperial Valley. The deepest of these was drilled to 12,313 feet near Holtville, another to 8,350 feet near Westmoreland, another to 7,323 feet near Heber, and still another to 8,647 feet in the Superstition Hills. All encountered nonmarine sands and clays, from top to bottom, with some lacustrine beds in the uppermost 3,000 feet. The marine Imperial formation either was not reached in any of these wells, or is represented in the section by deltaic sediments deposited by the Colorado River.

GEOLOGIC STRUCTURE

Northeastern Coachella Valley

San Andreas Fault Zone. The San Andreas fault follows a uniformly straight course through the Indio Hills southeastward to the northeast shore of Salton Sea. It probably is vertical or nearly so. In the Indio Hills the fault comprises two branches that merge southeastward. Both branches form low scarps that generally face northeastward in the northwest part of the hills and southwestward in the southeast part, which suggest that the hills have been sliced by right lateral movement on the fault.

Throughout the course of the fault right lateral movement, or relative southeastward displacement of the northeast block, is indicated by several offset washes and by sharp east-trending drag folds in the adjacent Cenozoic sediments. The sediments near the fault are invariably upended, contorted, or sheared. The total horizontal displacement since Pliocene time probably amounts to several miles, as the stratigraphically equivalent rocks on either side of the fault in the Mecca and Durmid Hills differ markedly.

In the Mecca Hills, northeast of the San Andreas fault, are several steeply dipping faults that are nearly parallel to and related to the San Andreas. Each shows upward and probable northwesterly displacement of the block southwest of it.

Folding in the Cenozoic Sediments. The Indio Hills is a large anticlinal upwelling of the Coachella Valley sedimentary fill along the San Andreas fault zone. The northwestern and southeastern parts of the hills are anticlinal, with axes that trend approximately N. 70° W. In the Mecca Hills, the Palm Spring formation on the west side of the fault is upended and wrinkled into tight folds that trend N. 70° W, and the overlying Ocotillo conglomerate is tilted steeply valleyward. East of the fault the Tertiary sediments are compressed into the large Mecca Hills anticlinal uplift, and sheared Orocopia schist is exposed at the structurally highest point in Painted Canyon. In the axial portion of this fold the sediments are buckled into numerous tightly compressed minor folds that are arranged en echelon and trend N. 75° W. as compared to the N. 50° W. trend of the major fold axis and an associated fault.

Along the northeast side of Salton Sea, 6,000 feet of incompetent lacustrine beds are upended on the southwest side of the San Andreas fault. They are tilted steeply away from the fault, and are buckled into numerous small, tight folds with axes that trend N. 75° W. as compared to the N. 50° W. bearing of the fault. These obviously are a result of right lateral drag movement on the fault.

Northwestern Imperial Valley

San Jacinto Fault Zone. The San Jacinto fault is parallel to and similar to the San Andreas fault, but is far more complex. It is essentially a zone of discontinuous faults in a belt 4 to 6 miles wide. The faults generally are vertical, and are marked by long, straight scarps that face mostly to the southwest. The main San Jacinto fault is strongly developed at the northeast edge of Borrego Valley, where it forms a high, southwest-facing scarp. Aligned with this fault in areas to the southeast are the Superstition Mountain, Superstition Hills, and Imperial faults, the last-named of which extends southeastward into Mexico.

The Clark, Buck Ridge, and Santa Rosa faults branch off eastward from the San Jacinto fault, and extend through the southwest slope of the Santa Rosa Mountains into Clark Valley. Aligned with these faults to the southeast is the San Felipe Hills fault along the southwest edge of the San Felipe Hills.

The Santa Rosa Mountains and San Felipe Hills were elevated along this group of faults, which are a part of the general San Jacinto fault zone. The major movements on most, if not all, of the northwest-trending faults of the San Jacinto zone are right lateral, and vertical movements are either apparent or local, and commonly are reversed. Physiographic evidence of right lateral movement is present along the San Jacinto, Clark, and Buck Ridge faults north of Borrego Valley, chiefly in the form of offset canyons, and structural evidence is furnished southeastward from Clark Valley by numerous tight, east-trending folds in the Cenozoic strata.

Evidence of recent movements along several faults of the San Jacinto zone is not confined to the occurrence of straight scarps and offset gullies. On the Clark fault east of Clark Lake is a 300-foot, northeast-facing scarp in the alluvium. Recent breaks along the Superstition Hills fault were noted in February 1951 by Joseph Ernst, who reports (oral communication, August 1953): "Recently formed surface fractures developed along 2 miles of the Superstition Hills fault, on which a mild earthquake reported in Imperial Valley on January 29, 1951, probably originated, were from 50 feet to 100 feet long, generally vertical, gaping to ¼ inch. The fractures formed en echelon along the course of the fault, trending N. 20° W. as compared to the N. 50° W. trend of the fault." The severe earthquake of May 18, 1940, in Imperial Valley was caused by a movement on the Imperial fault. Roads, fences, and rows of citrus trees were offset laterally on this fault, with the northeast block displaced relatively southeastward. There was no observable vertical displacement. Horizontal displacement amounted to 3 feet near Imperial, 6 feet east of El Centro, and to as much as 13 feet near Calexico.

Minor vertical, northeast-trending cross faults are present within or near the San Jacinto fault zone in the Borrego Badlands and in the Superstition Hills. Associated with these faults are many tiny, east-trending, tightly squeezed drag folds, which indicate a left lateral drag or relative southwestward displacement of the northwest blocks.

Folding in the Cenozoic Sediments. The structure of the Cenozoic sediments exposed from the Santa Rosa Mountains southeastward through the Superstition Hills is extremely complex. Around the southeastern Santa Rosa Mountains the sediments are arched into the broad Santa Rosa anticline, which plunges southeast. This fold is cancelled out southeastward by the Borrego synclinorium, which plunges westward toward Clark Valley. South of this synclinal structure is the San Felipe anticlinorium, the major axis of which bears east-west through Borrego Mountain and the San Felipe Hills. At Borrego Mountain this anticlinal uplift is cut by the San Jacinto fault and its branches, and diorite is exposed west of the main fault; from this area the fold plunges and veers northwestward toward Borrego Valley. The recency of movement on this structure is indicated by several northeast-trending minor folds developed in the older alluvium across San Felipe Wash west of Borrego Mountain.

East of Borrego Mountain the San Felipe anticlinorium plunges eastward through the San Felipe Hills. The major axis is offset by right lateral movement along the San Jacinto and San Felipe Hills faults. Superimposed on the above-described major folds are innumerable minor, east-trending folds. These are especially abundant along the San Jacinto and San Felipe faults, or in areas where these faults die out southeastward, and obviously are a result of right lateral drag along these major faults.

The Superstition Hills is an anticlinal uplift on the northeast side of the Superstition Hills fault, and the northern part of this uplift is a series of many small, east-trending folds in the Brawley formation. These are developed en echelon adjacent to the minor northeast-trending faults. In the low, flat area between the Superstition Hills and the San Felipe Hills are several additional northeast alignments of tiny, east-trending folds, some of which probably are of relatively recent development.

Southwestern Imperial Valley

Elsinore Fault Zone. The Elsinore fault zone is even more complex than the San Jacinto fault zone. It covers a wider area, involving a strip of low mountains, 8 to 12 miles wide, that includes Granite Mountain, Vallecito-Fish Creek Mountains, Carrizo Valley, and the Coyote Mountains. The Elsinore fault forms the southwest margin of this block, and is the largest individual fault. The Earthquake Valley and San Felipe faults branch off eastward from it, and themselves feather out into many branches.

Granite Mountain and the Vallecito-Fish Creek Mountains are composed of massive plutonic rocks that have been shattered and broken into numerous fault blocks, probably by lateral shear or torsion movement on and between the major faults. The western parts of these mountains were elevated along the Elsinore and Earthquake Valley faults, and the eastern parts along the San Felipe fault system, to form a tectonic shear block. In the Vallecito and Fish Creek Mountains are several northeast-trending, steeply dipping normal faults, most of which show elevation on their northwest sides. The largest of these forms the steep southeast front of the Fish Creek Mountains. These faults probably are a result of northwestward tilting of major blocks of dominantly granitic rocks.

The Coyote Mountain range was elevated along the Elsinore fault and tilted northward. The upended metasediments of this range strike southeast in the Carrizo Mountain portion, thence curve southward and nearly westward into the Elsinore fault. The anomalous westerly trend may have been produced by right lateral drag on the fault. In the western part of the range are many minor faults that trend south of west, parallel to the bedding of the metasediments, and that probably have left lateral offsets.

Vertical displacements along the Elsinore fault are locally great, but probably are more apparent than real, as the distribution of rock types indicates that they are twice reversed. A great amount of right lateral movement is indicated by tight, east-trending drag folds in the Cenozoic sediments on the south side of the Coyote Mountains.

Folding in the Cenozoic Sediments. On the north side of Carrizo Valley the sedimentary rocks dip homoclinally southwest to form the only completely exposed sequence of Cenozoic strata in Imperial Valley. Southward from Carrizo Wash the structure is complex. In the northwestern Coyote Mountains the sediments dip northwest. As this range was elevated along the Elsinore fault on its southwest base, the Tertiary sediments on the south side of the fault are upended and wrinkled into sharp folds that strike into it from the west, indicating right lateral drag. The Imperial and Palm Spring formations, as exposed from the eastern Coyote Mountains southeastward to Signal Mountain, are compressed into many open folds that generally trend and plunge northeastward. The folds are more numerous and complex adjacent to the Laguna Salada fault, where even the older alluvium is locally deformed.

Regional Tectonics

The regional trend of the upturned metamorphic rocks is northwest in the mountains bordering the Imperial Valley region, indicating that prior to invasion of the plutonic rocks, the metamorphic rocks were folded by a great regional northeast-southwest compressive stress.

The complex of basement rocks evidently reacted to late Cenozoic stresses as a comparatively rigid mass, except where it was rendered semi-pliable by shearing along the major fault zones. The overlying sedimentary fill, in contrast, reacted as a pliable cover. The strain pattern in the Imperial Valley region is clearly defined. The primary strain features are the northwest-trending high-angle faults developed along the San Andreas, San Jacinto, and Elsinore zones. Movements along these faults are predominantly right lateral, with relative southeastward displacements of the northeast blocks, and vertical movements are local or only apparent. The secondary or subsidiary strain features are: (1) the northeast-trending minor faults with left lateral movements, probably formed by slight clockwise rotation of northeast-trending blocks that in turn was caused by right lateral drag along the major northwest-trending faults; (2) northeast-trending normal faults; and (3) series of generally east-trending folds developed en echelon in the sedimentary fill along or near the major fault zones. This strain pattern in general is similar to that of the Transverse Range belt of southern California, except that thrust faults are not developed and the upended Cenozoic strata are not overturned.

The primary overall strain in the Imperial Valley region during late Cenozoic time has been torsional in a clockwise direction. The northeastern part of the region has moved southeastward relative to the southwestern part. This strain could result only from a general northwest-southeast clockwise torsional stress.

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3. GEOLOGY OF THE PENINSULAR RANGE PROVINCE, SOUTHERN CALIFORNIA AND BAJA CALIFORNIA*

By Richard H. Jahns †

GENERAL FEATURES

The Peninsular Range province is a well-defined geologic and physiographic unit that occupies the southwestern corner of California and extends southeastward to include the Baja California peninsula (fig. 1). It is characterized by elongate ranges and valleys whose general northwesterly trend is terminated abruptly on the north by the east-west grain of the Transverse Ranges. The part of the province that lies above sea level is approximately 900 miles long, 140 miles in maximum width, and 55 miles in average width. An additional large part is mainly submerged beneath the Pacific Ocean, and is represented by Santa Catalina, Santa Barbara, San Nicolas, and San Clemente Islands.

The higher parts of the province, which are underlain chiefly by igneous and metamorphic rocks of pre-Cenozoic age, include the Santa Ana, San Jacinto, Santa Rosa, Agua Tibia, and Laguna Mountains in California, and the Sierra Juarez, Sierra San Pedro Mártir, and other ranges that form the "backbone" of Baja California (fig. 1). San Jacinto Peak, near the north end of the province, rises to an altitude of 10,805 feet, and La Providencia Mountain, in northern Baja California, reaches an altitude of 10,126 feet. These and other high mountain masses occupy the northeastern and eastern parts of the region, and are bounded from the adjoining Colorado Desert region and the Gulf of California on the east by spectacular scarps, 6,000 feet to more than 9,000 feet high, that bear a striking resemblance to the east face of the Sierra Nevada. Most of these scarps are disposed en echelon, and mark the subparallel traces of major zones of faulting.

The general topography of the region becomes less rugged toward the west and southwest, where it is characterized by remarkable combinations of subdued upland surfaces (figs. 4, 11), prominent ridges and peaks (figs. 4, 8), longitudinal valleys that are in part fault-controlled (fig. 11), numerous basins and broad, mature valleys (fig. 8), and some tortuous, very steep-walled canyons (fig. 6). Farther west is an irregular coastal plain, a few hundred feet to as much as 30 miles wide, on which marine and fluviatile terraces are prominently displayed (fig. 2). This plain is underlain chiefly by sedimentary and volcanic rocks of late Mesozoic and Cenozoic age, and its surface is interrupted here and there by ridges and other projections of older, more resistant rocks.

The region as a whole presents an asymmetric transverse profile whose relatively long and gentle westerly slope is considerably broken in detail (fig. 3). Some of the major topographic irregularities are ascribable to erosion along or adjacent to fault zones, and similar fault-controlled irregularities evidently are present beneath the sea floor on the continental borderland (Shepard and Emery, 1941). The Los Angeles basin, at the northwestern end of the province, marks a broad area of Cenozoic marine sedimentation. In many respects it resembles basins that lie farther north, in the western part of the Transverse Range province (see Bailey and Jahns, Contribution No. 6, this chapter), but its principal structural features have the characteristic northwesterly trend of the Peninsular Ranges. The Desierto de Santa Clara marks a somewhat similar basin in central Baja California (fig. 1).

The province is one of great climatic contrasts. Annual precipitation ranges from only a few inches in the arid valleys and adjacent slopes along its eastern margin to as much as 50 inches on some of the highest mountain ranges. The southern California coastal area receives 11 to 18 inches of rainfall per year, but the amount decreases southward to less than 5 inches along parts of the Baja California coast. The climate ordinarily is mild in the northern coastal areas, but elsewhere the ranges of temperature are greater, and locally are extreme.

The pattern of vegetation in the region is highly varied, and representatives of nearly all the major life zones are present (see Bailey, Contribution No. 2, Chapter I). Typical desert forms occur in the lower interior areas, and are widespread in Baja California. In contrast, the highest mountain ranges are timbered, and park-like stands of pine and cedar are present as far south as the crest of the Sierra San Pedro Mártir. Dense growths of brush cover many of the mountain slopes (figs. 4, 7), and over large areas form such a serious obstacle to travel on the ground that one frustrated investigator was moved to write, "Where the steepness does not forbid the way, the chaparral everywhere disputes it."

Except for the northern coastal areas, the region is sparsely populated, and large parts of Baja California are essentially uninhabited. The geology of the province as a whole has been investigated only in reconnaissance, and detailed studies of moderately large areas have been restricted to the portion that lies north of the international boundary. The most general reports on large parts of the region are those of Beal (1948), Darton (1921), Ellis and Lee (1919), Fair-

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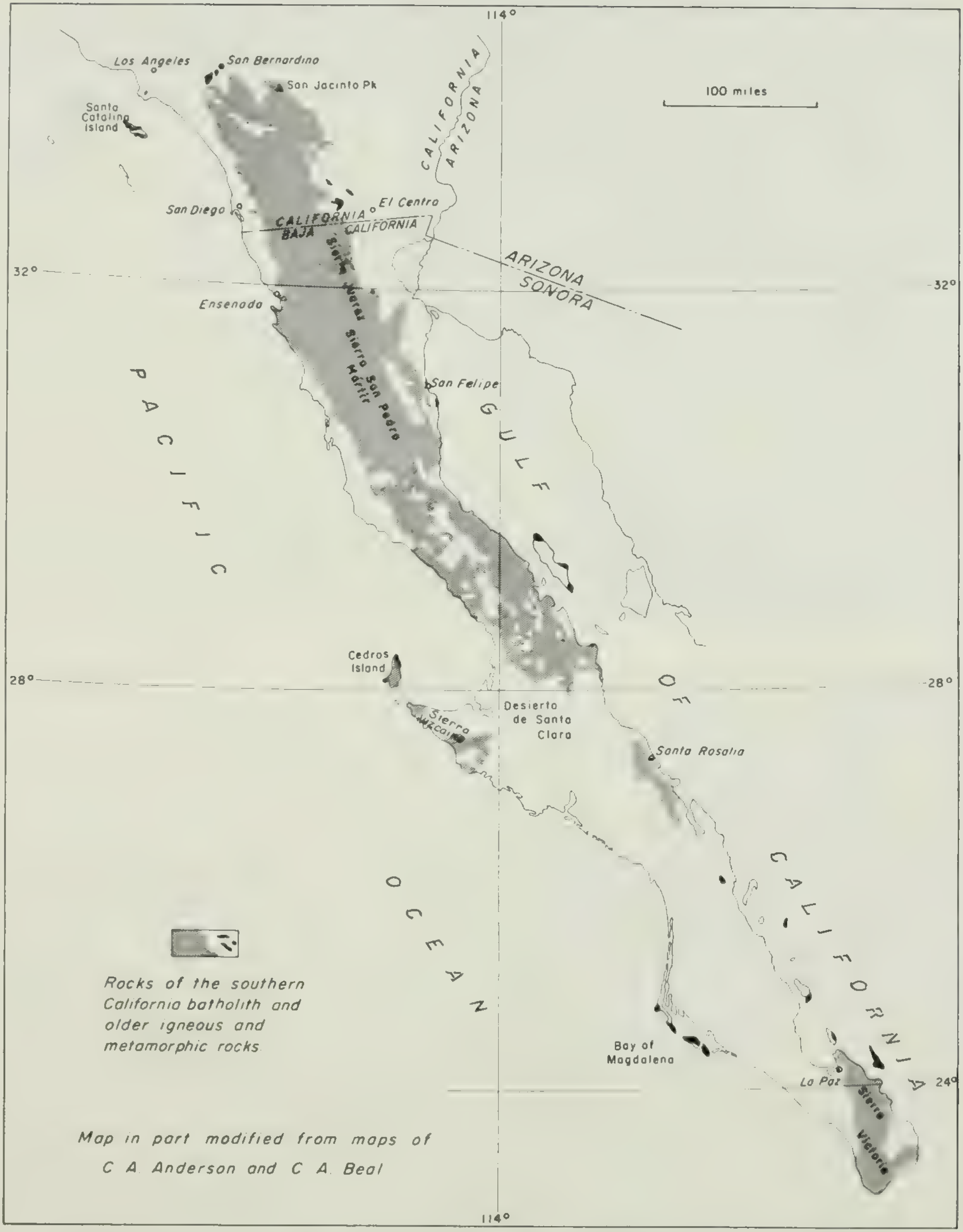

FIGURE 1. Map of the Peninsular Range province, southern California and Baja California, showing the distribution of rocks that lie beneath the great Mesozoic unconformity.

banks (1893), Larsen (1948), Merrill (1914), Nelson (1922), Reed (1933), Sauer (1929), Waring (1919), and Wisser (1954). The published record includes numerous other contributions that deal with specific areas, problems, or mineral deposits, and a sampling of these is provided in the list of references at the end of this paper.

Despite the present incompleteness of geologic data for the region as a whole, it is possible to summarize the general nature and occurrence of rock types and major structural features within it, and to outline the principal episodes of its geologic history. Many of the features that bear critically upon this history are known only from Baja California, and it is mainly for this reason that a brief treatment of this large peninsula is included in the following pages.

THE GEOLOGIC SECTION

General Relations

The rocks of the Peninsular Range province, like those in many other parts of southern California, can be readily grouped into two major divisions that are everywhere separated by a profound unconformity. Moderate to very great differences in lithology, structure, and degree of metamorphism distinguish the rocks beneath this break from those that lie above it, even though in some areas the respective rocks represent closely adjacent parts of the general geologic column. The oldest rocks above the unconformity are marine strata of Upper Cretaceous age, and the youngest rocks beneath it are plutonic types that are demonstrably intrusive into marine strata of Lower Cretaceous and earliest Upper Cretaceous age at several localities in western Baja California.

The exposed rocks in the eastern and other mountainous parts of the province are dominantly igneous, metasedimentary, and metavolcanic types of Paleozoic and Mesozoic age (plate 3). Most abundant among these members of the older sequence are gabbroic to granitic plutonic rocks that constitute the great southern California batholith. The metamorphic rocks and some other igneous rocks antedate this batholith, and form a widespread but generally subordinate part of the crystalline terrane.

The younger sequence comprises marine and nonmarine strata of Upper Cretaceous, Tertiary, and Quaternary age, as well as volcanic rocks of Tertiary and Quaternary age. Nearly all of the marine strata are in the coastal parts of the province, where they are dominantly clastic and form a fairly continuous apron, a few hundred feet to a few thousand feet thick, that slopes gently in a seaward direction. Despite its gross simplicity, however, the section shows numerous complications of stratigraphy and structure. It thickens enormously in the Los Angeles basin, where it amounts to 40,000 feet or more, as well as in at least two other large basins in Baja California. These thick sequences are broken by major unconformities, and paleontologic evidence suggests some markedly contrasting environments of deposition. In several areas the strata have been considerably warped and folded.

Marine incursion along the northeastern margin of the province is represented mainly by remnants of Upper Tertiary clastic strata in the Imperial Valley area and adjacent parts of Baja California. Other marine sections appear farther south, along the Gulf of California.

Nonmarine strata, chiefly fluviatile in origin, are scattered through the interior parts of the province, where they commonly are preserved as the upper parts of structurally low fault blocks. Typical of these occurrences are interbedded clastic sediments, clay, and lignite of Paleocene age in the Corona-Elsinore area and nearby parts of the Santa Ana Mountains, and clastic sediments of late Tertiary and Quaternary age in the Redlands-San Jacinto area farther northeast (plate 3). A very thick section of dominantly clastic nonmarine strata is widely exposed along the western margin of the Coachella and Imperial Valleys, where it apparently represents intermittent deposition since mid-Miocene time. Nonmarine sedimentation in the coastal areas is recorded mainly by strata of Paleocene to Miocene age, some of which are interbedded with marine sediments.

Volcanic rocks of Miocene age are exposed in many parts of the coastal area and along the western margin of the Imperial Valley, and are widespread in central and southern Baja California. They are mainly shallow intrusives, flows, and pyroclastic accumulations of andesitic and basaltic composition. Younger basaltic rocks, of late Tertiary and Quaternary age, form typical mesa cappings in the Santa Ana and Santa Margarita Mountains, and are extensively exposed in parts of Baja California.

Rocks Beneath the Great Unconformity

Older Sedimentary and Volcanic Rocks. The oldest exposed rocks in the region are sedimentary strata and subordinate interlayered volcanic rocks that have been mildly to severely metamorphosed. In general they appear as small to very large inclusions, pendants, and screens within or around masses of younger plutonic rocks, and plainly are remnants of a very thick and once-extensive terrane that was broken up and locally much deformed by widespread igneous invasion.

This old terrane is exposed over large areas in the San Jacinto, Santa Rosa, and Coyote Mountains, where quartzite, crystalline limestone, phyllite, hornblende and mica schists, and quartz-feldspar schists and gneisses may reach an aggregate thickness as great as

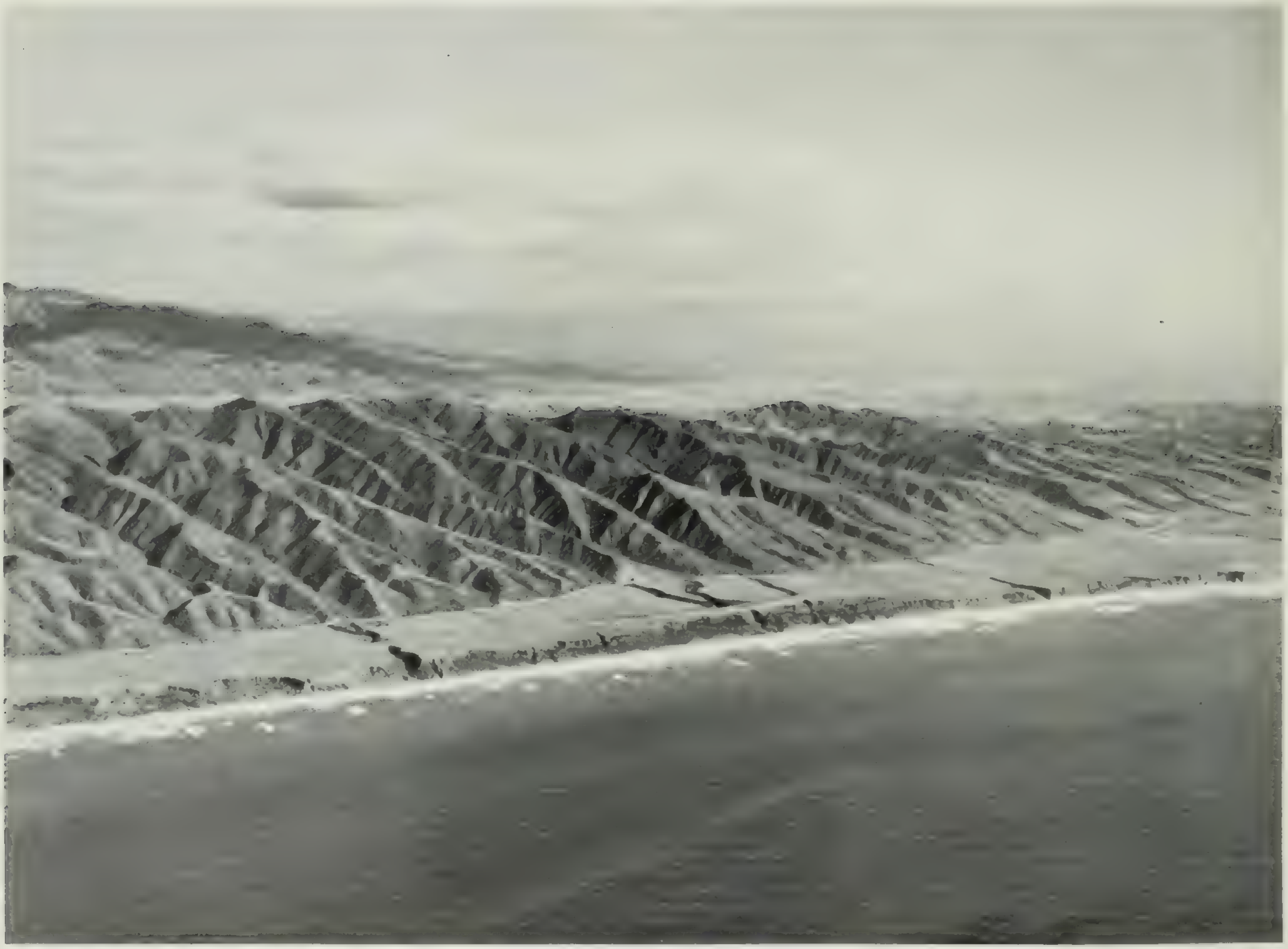

FIGURE 2. Aerial view east-northeastward from the coastline immediately south of San Onofre, showing prominent low marine terrace. Note the numerous bench-like remnants of several higher terraces that were cut into the foreground ridge of Tertiary sedimentary rocks. Santa Margarita Mountains are at extreme left, and San Marcos Mountains are in center distance. *Photo by J. S. Shelton and R. C. Frampton.*

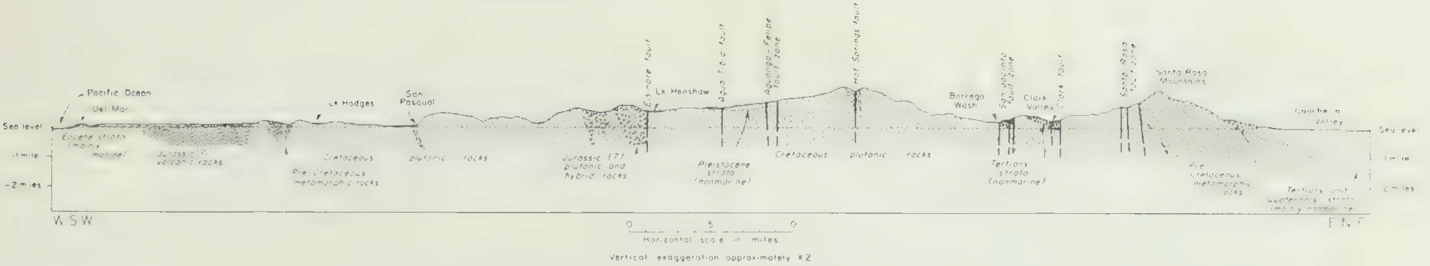
Pacific Ocean
Del Mar
Lk Hodges
San Pasqual
Elsinore fault
Lk Henshaw
Agua Tibia fault
Aguanga - Felipe fault zone
Hot Springs fault
Borrego Wash
San Jacinto fault zone
Clark Valley
Clark fault
Santa Rosa fault zone
Santa Rosa Mountains
Coachella Valley
Sea level
-1 mile
-2 miles
Eocene strata (mainly marine)
Jurassic (?) volcanic rocks
Pre-Cretaceous metamorphic rocks
Cretaceous plutonic rocks
Jurassic (?) plutonic and hybrid rocks
Pleistocene strata (nonmarine)
Tertiary strata (nonmarine)
Pre-Cretaceous metamorphic rocks
Tertiary and Quaternary strata (mainly nonmarine)
W S W
E N E
0 5 10
Horizontal scale in miles
Vertical exaggeration approximately ×2

FIGURE 3. Cross section of the Peninsular Range province from Del Mar to the north end of the Salton Sea.

22,000 feet. These rocks may be in part correlative with Paleozoic strata of similar lithology that are exposed in the northern part of the San Bernardino Mountains, and possible fossil material that further suggests a Paleozoic age was obtaned by Miller (1944, pp. 21-25) from localities a few miles southeast of Palm Springs. Similar metamorphic rocks are widely distributed in areas to the west and northwest (pl. 3), and "reasonably well-preserved" fossils of apparent Mississippian age have been found in at least one locality a short distance south of Winchester (Webb, 1939).

Farther west, in the Santa Ana, Elsinore, and Santa Margarita Mountains, is a section of mildly metamorphosed strata, perhaps as much as 20,000 feet thick, that is composed mainly of gray to brownish argillite and slate, with subordinate feldspathic quartzite and a few lenses of limestone and conglomerate. These rocks, termed the Bedford Canyon formation by Larsen (1948, pp. 18-22), are sparsely fossiliferous and are generally regarded as Triassic in age. They are overlain unconformably by slightly metamorphosed agglomerates, breccias, tuffs, and flows that range in composition from andesite to latite and quartz latite. These volcanic rocks, together with some fine-grained argillaceous sedimentary rocks that are interlayered with them, are known as the Santiago Peak volcanics (Larsen, 1948, pp. 22-27), and also have been termed the Black Mountain volcanics in areas to the south (M. A. Hanna, 1926, pp. 199-204). They appear to be many thousands of feet thick, and have been tentatively assigned to the Jurassic by most investigators. They are gray, greenish gray, and reddish to purplish brown, and characteristically form rough slopes with many ragged, irregular, dark-appearing cliffs.

The boundary between the Bedford Canyon formation and the older rocks to the east has not been established precisely, as the metamorphism of the younger rocks increases progressively in an easterly direction from the type area in the Santa Ana Mountains, and no pronounced lithologic break has been recognized. Larsen (1948, pp. 17-18) postulates a fault between these major units in the area south of Winchester (plate 3), but points out that rocks of Paleozoic age probably are present in areas southwest of this contact.

Metasedimentary rocks also are widespread farther south in the province, especially in the Agua Tibia and Laguna Mountains. Here they are known mainly as the Julian schist (Merrill, 1914, pp. 638-642; Hudson, 1922, pp. 182-190; Donnelly, 1935, pp. 337-340), and consist of quartz-mica schist and feldspathic to vitreous quartzite, with minor amphibolite, quartz-mica-amphibole schist, metaconglomerate, and recrystallized limestone. The different rock types commonly intergrade along and across the strike, and appear to represent an original series of shallow-water sediments. Most of the amphibole-bearing rocks evidently were derived from flows and tuffs of intermediate to basic composition. It has been suggested by Fairbanks (1893, pp. 82, 87), Hudson (1922, pp. 188-190), and others that the Julian schist may correspond, at least in part, to the Triassic section of the Santa Ana Mountains, but this correlation should be regarded as tentative. Some of the schist sequence may well be of Paleozoic age.

Similar metamorphic rocks are widespread in the northern half of Baja California, where fine-grained schists are dominant. These rocks, like the Julian schist, may well represent both Paleozoic and lower Mesozoic sedimentation.

A distinctly different assemblage of mildly metamorphosed schists, chert, limestone, and associated igneous rocks underlies much of the western part of the province, where it is largely concealed beneath the waters of the Pacific Ocean. These rocks are best exposed in the Palos Verdes Hills, at the western margin of the Los Angeles basin, and on several of the banks and islands offshore; in Baja California (fig. 1) they have been noted from the Sierra Vizcaino (Beal, 1948,

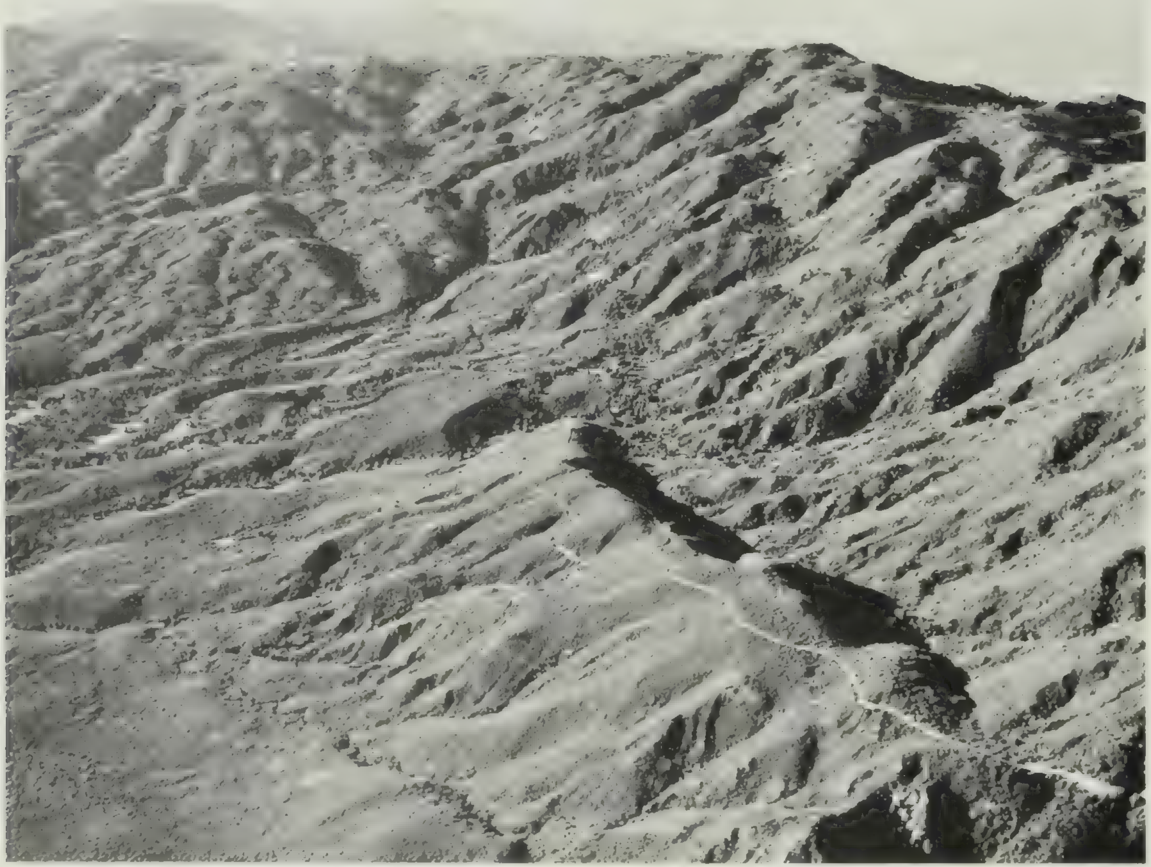

FIGURE 4. Aerial view west-northwestward over a part of the Agua Tibia Mountains, showing typically irregular, brush-covered terrain. Barker Valley is in foreground at right, and Palomar Observatory is in middle distance at left. Note the alignment of benches, gulches, light-colored grassy areas, and clusters of trees that mark the trace of the Agua Tibia fault extending away from the observer in center of view. *Photo by J. S. Shelton and R. C. Frampton.*

pp. 36-37), Cedros Island and several smaller islands to the northwest (G. D. Hanna, 1925, 1927), and from the western margin of the Bay of Magdalena (Hirschi and De Quervain, 1933).

The most abundant rock types are fine-grained chlorite-bearing schists that commonly contain epidote, actinolite, muscovite, and albite, and that are particularly distinguished by the presence of glaucophane and lawsonite. Bodies of metavolcanic rocks and altered and metamorphosed intrusive rocks, chiefly serpentine and dioritic to gabbroic types, are widespread. The rocks of this terrane may be older than the metamorphic assemblage farther east, but it seems more likely that they represent a southern extension of the Mesozoic Franciscan group of California, as suggested by Beal (1948, pp. 107-108) and others.

Older Intrusive and Migmatitic Rocks. Hypabyssal intrusive rocks that probably are related to the Santiago Peak volcanics (Larsen, 1948, pp. 27-32) transect the Bedford Canyon formation in the Santa Ana Mountains, in the area north of Elsinore Lake, and in areas farther south. They are older than the more widespread plutonic rocks of the southern California batholith, which are described farther on. Together with the Santiago Peak volcanics, these older intrusives occupy a north-northwestward trending belt more than 80 miles long and 2 to 12 miles wide (plate 3). They are fine to medium grained, and include such rock types as gabbro, gabbro porphyry, diabase, tonalite, granodiorite, and dacite, latite, and quartz latite porphyries. Most of them resemble the Santiago Peak volcanics in general composition and degree of metamorphism.

In the eastern parts of the province are numerous irregular plutonic masses, some of them very large, of tonalite and granodiorite that also antedate the rocks of the southern California batholith. Most of these rocks have a well-defined gneissoid structure, and many of them are extensively granulated and otherwise deformed on a small scale. The Stonewall granodiorite (Hudson, 1922, pp. 191-193; Merriam, 1946, pp. 230-231; Everhart, 1951, pp. 61-64) is a widespread representative of this group in the Laguna Mountains and adjacent areas, and the highly sheared and foliated granodiorite that is prominently exposed on the west side of Palm Canyon, in the San Jacinto Mountains, is another characteristic type. Similar rocks appear in many parts of the higher ranges in Baja California.

The larger plutons commonly are in part bordered by broad zones of injection gneiss, contact breccias, and other migmatitic rock types. These mixed rocks plainly were derived from the older metamorphic rocks already described, and they underlie large areas in the eastern ranges, both in California (Donnelly, 1934, pp. 337-340; Merriam, 1946, pp. 231-232; Everhart, 1951, pp. 64-65) and northern Baja California (Woodford and Harriss, 1938, pp. 1310-1313).

Younger Sedimentary and Volcanic Rocks. Fossiliferous stratified rocks of Lower Cretaceous and early Upper Cretaceous age are known from several areas in western and northwestern Baja California, where they are separated from younger Upper Cretaceous strata by a marked angular unconformity. They have been referred to as the San Fernando formation (Beal, 1948, pp. 38-40) and the Alistos formation (Santillán and Barrera, 1930), and consist of shale, sandstone, conglomerate, and limestone with interlayered tuff and other volcanic rocks of basic to intermediate composition. In places they have been mildly metamorphosed, and the section has been considerably folded.

These upper Mesozoic strata have been intruded by plutonic rocks that may well be parts of the southern California batholith, and hence they bear critically upon the problem of dating this great igneous mass. Farther east, in the Sierra San Pedro Mártir, rocks of the batholith are intrusive into the San Telmo formation, a thick sequence of slate, phyllite, quartzite, metaconglomerate, and volcanic rocks from which some fossils that "have a Mesozoic aspect" are reported (Woodford and Harriss, 1938, pp. 1306-1310). This sequence may be in part a metamorphosed equivalent of the San Fernando formation (Beal, 1948, p. 39), or it may be entirely older.

Rocks of the Southern California Batholith. A series of fine- to coarse-grained intrusive rocks constitutes the very large and complex batholith, termed the southern California batholith by Larsen (1941), that underlies much of the Peninsular Range province. It extends from the Jurupa Mountains, northwest of Riverside, to the southern tip of Baja California and points beyond, and hence it probably is more than 1,000 miles long. It is in part concealed by younger rocks, especially in Baja California, but appears to be at least 50 miles in average breadth. It thus is even larger than the Sierra Nevada batholith, and has the gross form of a gigantic, steeply dipping dike. The northern part of this great mass has become well known through the classic investigations of Larsen (1948; see also the summary in Contribution No. 3, Chapter VII, this volume).

The batholith is internally complex, and comprises many separate intrusive units, or plutons, that range in maximum outcrop dimension from a few hundred feet to several miles. Some of these are separated by straight or curved septa and screens of older metamorphic rocks, whereas others are directly juxtaposed along contacts that can be recognized only through detailed examination or can be inferred from differences in composition or internal structure of the plutons involved (fig. 5).

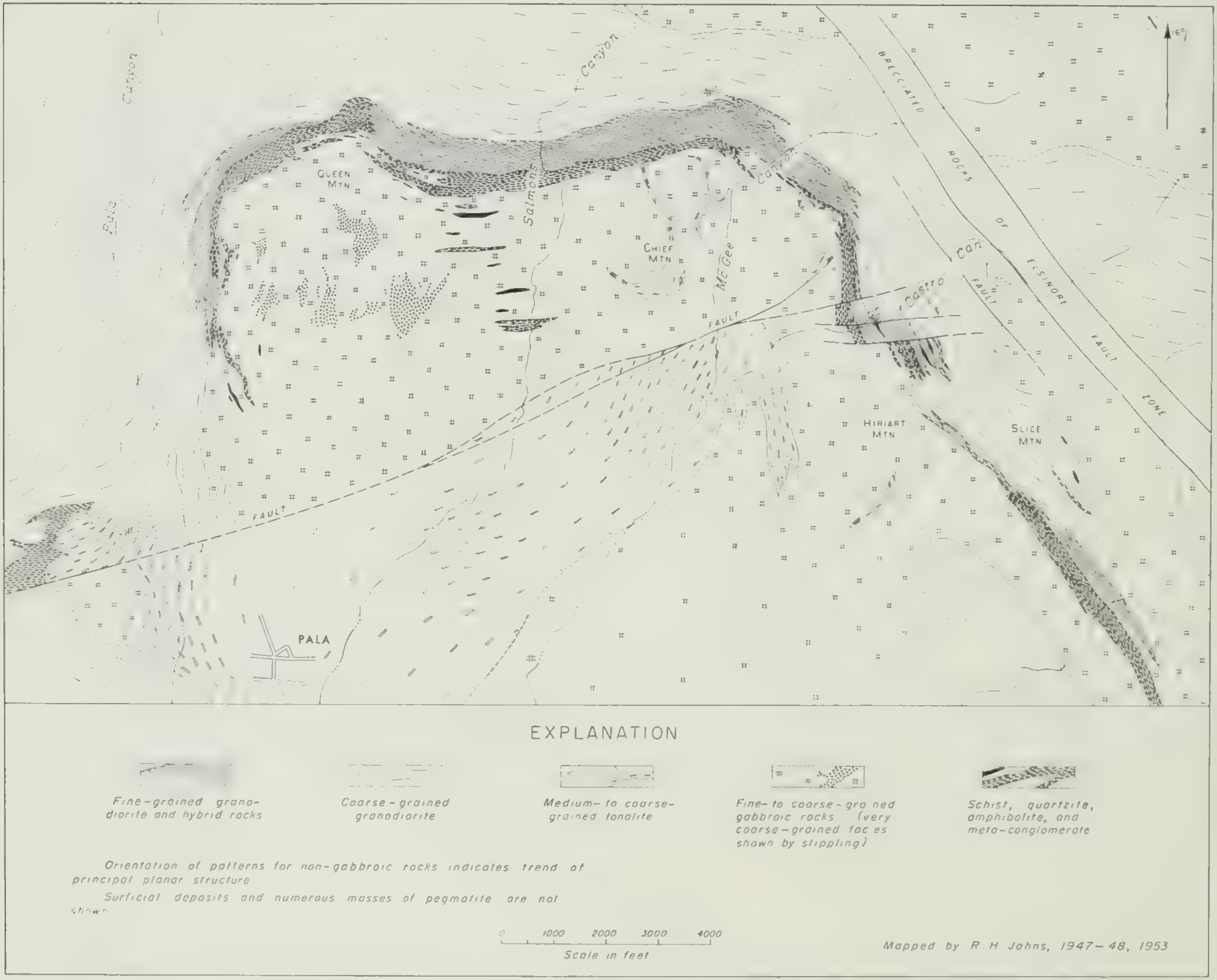
Pala Canyon
Salmons Canyon
Queen Mtn
Chief Mtn
McGee Canyon
Castro Can
Hiriart Mtn
Slice Mtn
Brecciated rocks of Elsinore fault zone
Fault
Pala
16°
EXPLANATION
Fine-grained granodiorite and hybrid rocks
Coarse-grained granodiorite
Medium- to coarse-grained tonalite
Fine- to coarse-grained gabbroic rocks (very coarse-grained facies shown by stippling)
Schist, quartzite, amphibolite, and meta-conglomerate
Orientation of patterns for non-gabbroic rocks indicates trend of principal planar structure
Surficial deposits and numerous masses of pegmatite are not shown
0 1000 2000 3000 4000
Scale in feet
Mapped by R H Johns, 1947–48, 1953

FIGURE 5. Geologic map of a part of the Pala district, showing typical relations between plutons of the southern California batholith.

The average composition of the entire batholith is in the tonalite range, and tonalite is by far the most abundant single rock type. From one pluton to another, however, the composition ranges from gabbro to granite, and the succession of intrusions appears to have been, with remarkably few exceptions, gabbro → basic tonalite → tonalite → granodiorite → quartz monzonite → granite. As pointed out by Larsen (Contribution No. 3, Chapter VII), five major rock types in the gabbro-to-granodiorite range constitute more than 90 percent of the exposed parts of the batholith in southern California, and also form nearly all of the large intrusive units. Individual rock types vary in composition and texture from place to place, but in a broad way they are so uniform that they can be readily identified in widely separated areas. The gabbroic rocks are relatively abundant in the western parts of the province, but are rare farther east, where leucocratic tonalites and granodiorites are predominant.

Tabular inclusions are present in many of the tonalites and granodiorites, and in places are so abundant that the rocks resemble flow-layered breccias. Some of the plutons are bordered by hybrid gneisses formed through invasion of the older metamorphic rocks by igneous material. In general these gneisses are much less extensive than the hybrid rocks that are related to the plutonic rocks of prebatholith age.

Dike rocks associated with the batholith are widespread, and include leucogranite, pegmatite, aplite, diorite, microtonalite, and porphyries of intermediate composition. Represented among the pegmatitic intrusives are the famous gem-bearing dikes of Riverside and San Diego Counties (Schaller, 1925; Jahns and Wright, 1951; Hanley, 1951; see also Contribution No. 5, Chapter VII).

The batholith probably is of early Upper Cretaceous age. It is believed by Larsen (1948, pp. 134-172; Contribution No. 3, Chapter VII) to have been formed from a slowly differentiating parent magma of gabbroic composition. Successive injections of this magma and its differentiates probably accompanied episodes of local to regional diastrophism, and yielded many large and relatively uniform bodies of gabbroic to granodioritic rock, as well as smaller bodies of rocks that represent a wider range of composition.

Metamorphism. Most of the pre-batholith rocks in the western part of the province have been only mildly metamorphosed, and they represent the greenschist facies of Eskola. This metamorphism is uniform over very large areas, and does not appear to be related to masses of igneous rocks; it probably antedates the emplacement of the southern California batholith. To the west, the low-rank metamorphic rocks give way abruptly to wholly different Franciscan-like schists and associated rocks that represent the glaucophane schist facies. To the east there is no such fundamental lithologic change, and instead the degree of metamorphism gradually increases; the slaty and phyllitic rocks, for example, grade into muscovite- and biotite-bearing schists.

The Paleozoic rocks in the eastern part of the province have been moderately metamorphosed in a regional sense, and correspond to the greenschist facies and the albite-epidote amphibolite facies. Among the more widespread minerals are biotite, muscovite, hornblende, garnet, and epidote. These rocks may have been metamorphosed prior to deposition of the Mesozoic rocks that later were themselves metamorphosed, but no compelling evidence for this has been recognized as yet.

Many of the rocks have been locally affected by contact metamorphism, especially where they occur as relatively thin inclusions and screens in rocks of the southern California batholith. The commonest products include feldspathic gneisses, hornfelses, tactite and other varieties of reconstituted limestone, and foliated rocks that contain garnet, amphibole, pyroxene, and sillimanite, either singly or in some combination. Contact metamorphism of calcareous rocks is especially well shown around intrusive masses of gabbro and serpentine in the Winchester area (Larsen, 1948, pp. 35-36), and around masses of tonalite or other plutonic rocks at the famous mineral occurrences of the Crestmore area near Riverside (see Burnham, Contribution No. 7, Chapter VII) and at numerous other localities in areas farther south (for example, Larsen, 1948, pp. 34-36; Fries and Schmitter, 1945).

Rocks Above the Great Unconformity

Upper Cretaceous Rocks. Clastic strata of Upper Cretaceous age rest unconformably upon the Bedford Canyon formation and the Santiago Peak volcanics in the Santa Ana Mountains. The section is nearly 6,000 feet in maximum thickness, and at its base is 300 to 400 feet of coarse, prevailingly reddish nonmarine conglomerate, the Trabuco formation of Packard (1916, p. 140). The remainder is marine, consists of interbedded conglomerate, arkosic sandstone, siltstone, and dark-colored shale, and in places is highly fossiliferous (Popenoe, 1941, 1942). In the Santa Monica Mountains to the west-northwest, Upper Cretaceous strata of similar lithology are about 7,000 feet thick, and commonly have been referred to the Chico formation.

Strata that apparently correspond to the upper part of the Santa Ana Mountains section are discontinuously exposed farther south along the coast, where they are only a few hundred feet thick. They are mainly sandstone, sandy limestone, and shale that is in part carbonaceous, and locally are underlain by redbeds that may be correlative with the Trabuco formation (see Hertlein and Grant, Contribution No. 4, this chapter). Still farther south, in coastal Baja

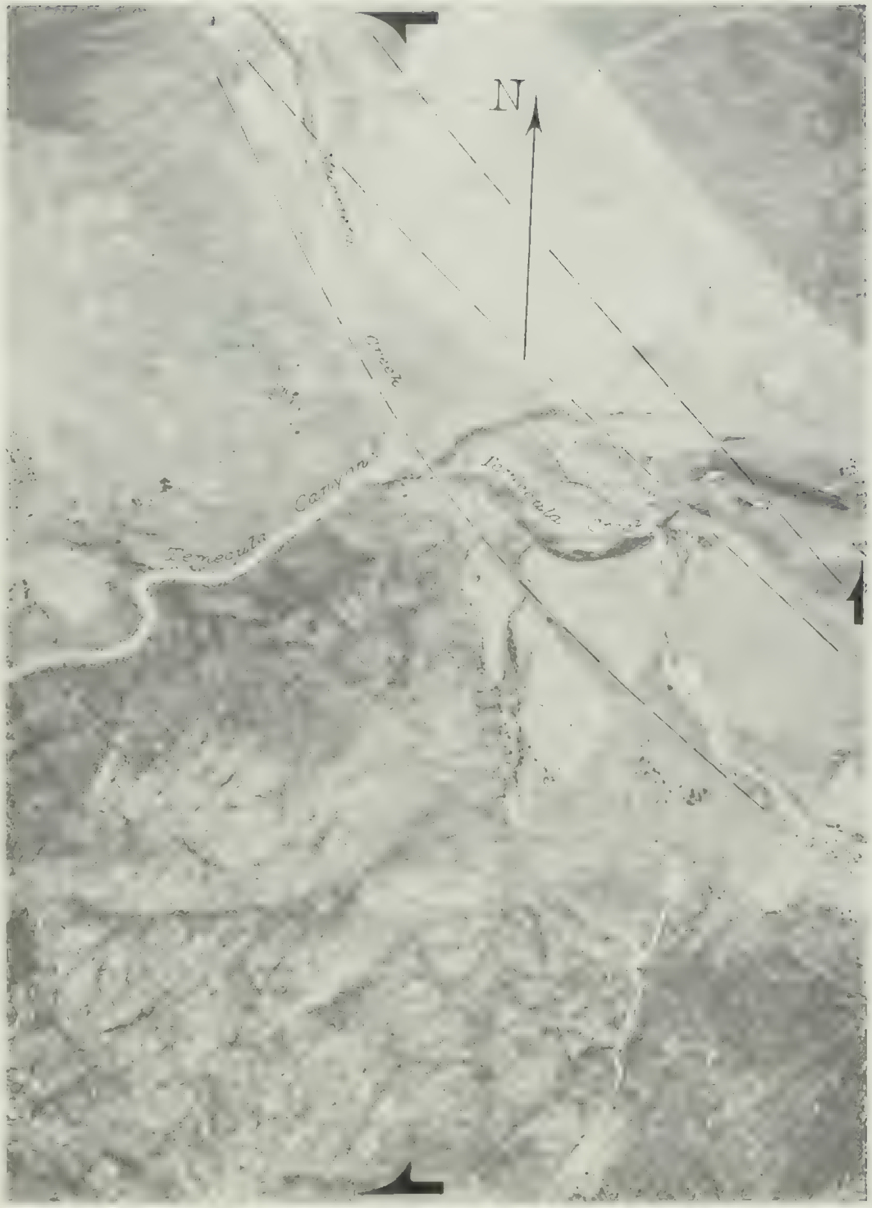

FIGURE 6. Vertical view of the area immediately south of Temecula, showing typical contrasts in weathering of different rocks. Jointed granodiorite forms rough slopes in south part of area, metamorphic rocks of Triassic age underlie the smoother slopes west of Murrieta Creek and north of the steep-walled Temecula Canyon, and arkose of Pleistocene age underlies the remainder of the area. Note the possible offset of Temecula Creek along the trace of one break (dashed line) in the Elsinore fault zone. *U. S. Department of Agriculture photo.*

California, Upper Cretaceous conglomerates, sandstones, shales, and coaly beds, known as the Rosario formation, rest with marked angular unconformity upon older Cretaceous strata (Beal, 1948, pp. 40-44). They are at least 2,500 feet in maximum thickness, and are almost wholly marine. Paleontologic evidence suggests that the exposed beds become younger toward the south, but, according to Beal (1948, p. 44), no complete section has been observed at any one locality.

Paleocene and Eocene Rocks. Sedimentary rocks of Paleocene and Eocene age rest upon a widespread erosional surface of low relief that was developed at the close of the Cretaceous period. Paleocene strata crop out in the Santa Ana Mountains, where they are about 1,400 feet in maximum thickness. They have been correlated by English (1926, p. 19) with the Martinez formation of areas far to the northwest, and have been termed the Silverado formation by Woodring and Popenoe (1945). They also appear in the Santa Monica Mountains, and probably underlie a considerable area in the eastern part of the Los Angeles basin (see Woodford, et al., Contribution No. 5, this chapter).

The Silverado formation rests unconformably upon Upper Cretaceous strata, and consists of nonmarine basal conglomerate, an overlying section of arkosic sandstone, clay, and lignite, and an upper section of marine sandstone. To the east and northeast, in the structurally complex area between Corona and Elsinore, Silverado strata of similar lithology may be as much as 4,000 feet thick. Here they rest mainly upon rocks of pre-Cretaceous age, and their base is marked by a buff to reddish clay that in a few places appears to have been derived *in situ* from the weathering of underlying igneous rocks.

Overlying the Silverado formation with apparent conformity are Eocene strata that have been correlated with the Tejon formation of areas farther northwest (English, 1926, p. 21). Known as the Santiago formation (Woodring and Popenoe, 1945), this sequence is about 2,700 feet in maximum thickness and consists mainly of thin- to massive-bedded sandstone with numerous lenses of siltstone and conglomerate.

Marine beds of middle and late Eocene age extend southward in the coastal part of the province as far as San Diego, where they are known as the La Jolla formation (M. A. Hanna, 1926). They are about 600 feet in maximum thickness, and are mostly sandstone and sandy shale whose lithology and contained fossils suggest deposition in warm waters under lagoonal and near-shore conditions. Above this formation is the Poway conglomerate (Ellis and Lee, 1919, pp. 67-68), which is chiefly nonmarine pebble to boulder conglomerate with irregularly interstratified marine sandstone. Vertebrate and invertebrate fossils obtained from this rather complex section indicate that it is largely of early upper Eocene age (see discussions in Hertlein and Grant, Contribution No. 4, this chapter, and in Durham, et al., Contribution No. 7, Chapter III).

As much as 7,000 feet of Paleocene and Eocene strata, termed the Tepetate formation, appears in three general areas on the Pacific slope of Baja California (Beal, 1948, pp. 44-51). The section is dominantly marine and almost wholly clastic. Sandstones, siltstones, and shales are most abundant, and commonly are variegated. Much of the formation appears to have been deposited under deltaic or other near-shore conditions, and at least some of the remainder probably is terrestrial. Scattered invertebrate fossils show relations to both Pacific Coast and Caribbean faunas (Beal, 1948, pp. 49-51), and indicate an age range from Paleocene to late Eocene.

Oligocene (?) and Lower Miocene Rocks. The Oligocene appears to have been an epoch of emergence in the Peninsular Range region, and strata of this age are essentially restricted to the Santa Ana Mountains and San Joaquin Hills. They are nonmarine, consist mainly of variegated sandstone, siltstone, and conglomerate, and appear to be correlative with the Sespe formation of the western Transverse Range province. They have yielded no fossils, but probably range in age from late Eocene to earliest Miocene (Woodford, et al., Contribution No. 5, this chapter).

These nonmarine beds lie upon the Santiago formation with apparent conformity, and are in part overlain by, in part intertongued with, gray to greenish gray and buff marine sandstone, conglomerate, and siltstone of the Vaqueros formation. The Vaqueros strata have yielded lower Miocene invertebrate fossils that suggest a shallow-water environment (Loel and Corey, 1932, pp. 51-60). The maximum combined thickness of the marine and underlying nonmarine units is slightly more than 3,000 feet.

A redbed section about 300 feet thick has been reported from the eastern, or gulf-coast, side of the Baja California peninsula by Beal (1948, pp. 51-53), who regards the strata as probably Oligocene in age. They lie beneath marine strata that may be equivalent to the Vaqueros formation (Loel and Corey, 1932, p. 160).

Middle and Upper Miocene Rocks. Rocks of middle and upper Miocene age are broadly distributed in the region, and represent sequences of volcanism and widespread marine and terrestrial sedimentation that are too complex to be detailed in this paper. In the coastal part of southern California the section is dominantly marine, and is best represented in the Los Angeles basin and adjacent areas (see Woodford, et al., Contribution No. 5, this chapter). It includes the coarsely clastic, shallow-water deposits of the Topanga formation, which are 2,000 to 7,500 feet thick; the organic to cherty siltstones and mudstones of the Monterey shale, which are about 4,200 feet in maximum thickness and represent deposition in both shallow and deep waters; the sandstones and partly organic shales of the Modelo formation, which are about 5,000 feet in maximum thickness; and the dominantly clastic deposits of the Puente formation, about 11,000 feet in maximum thickness.

The Topanga formation has been dated as middle Miocene, the Monterey shale as mostly middle Miocene and partly upper Miocene, and the Modelo and Puente formations as upper Miocene. Some of these units are in part equivalent, and Modelo and Puente are names applied to upper Miocene rocks of similar lithology in different areas.

Unusual conditions of sedimentation south of the Los Angeles basin are reflected by the San Onofre breccia (Woodford, 1925), which consists mainly of fragments, many of them slabs 5 feet or more long, of glaucophane schist and other rocks that are characteristic of the metamorphic terrane along the southwestern side of the province. This unit is about 2,500 feet in maximum thickness, and is thought to have been derived from a source that lay to the west, beyond the present coastline.

Volcanic flows, tuffs, and breccias, mainly of andesitic composition, are abundant in the middle Miocene section, and locally reach thicknesses of more than 3,000 feet. Most of these are described elsewhere in this volume by Shelton (Contribution No. 4, Chapter VII). Widely scattered dikes and plugs of similar composition probably are related to these rocks.

Miocene strata are absent from the coastal part of southern California south of the Santa Ana Mountains, but they reappear farther south in Baja California, where they have been divided into three formations, the San Gregorio, Ysidro, and Commondú (Beal, 1948, pp. 53-77). These units have an aggregate maximum thickness of more than 6,500 feet. The San Gregorio and Ysidro formations are marine, and consist mainly of diatomaceous, siliceous, and clay shales, as well as sandstones, tuffs, and impure limestones. The Commondú formation, which crops out over much of the southern half of the peninsula, is a thick sequence of lavas, agglomerates, and tuffs with interlayered clastic sediments of terrestrial origin.

Nonmarine strata of Miocene age are widely exposed along the western margins of the Coachella and Imperial Valleys, where they are about 2,800 feet in maximum thickness (see Dibblee, Contribution No. 2, this chapter). They comprise arkosic sandstone, conglomerate, and breccia, and as much as 100 feet of bedded gypsum is present at the top of the section in the northwestern part of the Fish Creek Mountains. Volcanic breccias, tuffs, and flow rocks of andesitic composition are exposed in several areas along the southwestern margin of the Imperial Valley.

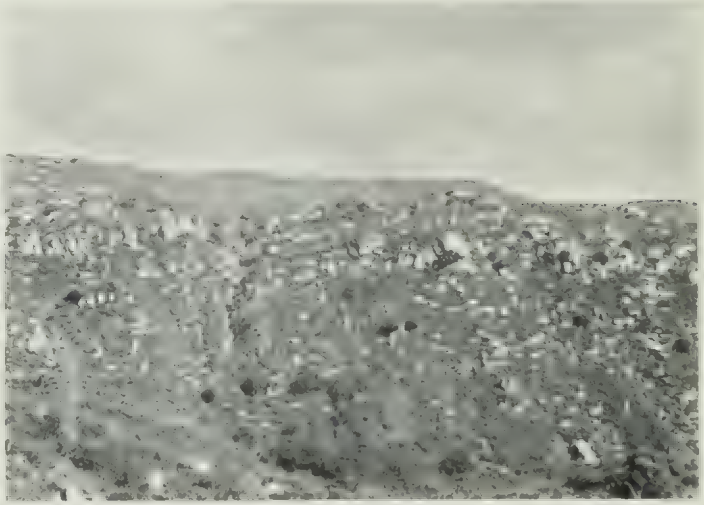

FIGURE 7. Bouldery exposures of granodiorite near the west end of the Agua Tibia Mountains. The rock is broken by two sets of steeply dipping joints, and by a third set of joints that dip gently from right to left.

Clastic nonmarine strata of probable Miocene age are exposed locally in the area north of San Jacinto, and also appear beneath andesitic volcanic rocks in the vicinity of Jacumba, near the international boundary.

Pliocene Rocks. Marine sedimentary rocks of Pliocene age are largely confined to the coastal area. As exposed in the marginal parts of the Los Angeles basin, they comprise siltstones, sandstones, and conglomerates of the Repetto and Pico formations (Woodford, et al., Contribution No. 5, this chapter), which are slightly more than 6,000 feet in maximum aggregate thickness. These rocks become somewhat finer grained toward the central part of the basin, where they are more than 10,000 feet thick; foraminiferal faunas indicate that much of this section was deposited in deep water (see Natland and Rothwell, Contribution No. 5, Chapter III).

Pliocene strata are widely exposed in the coastal areas to the south, including both sides of the Baja California peninsula. They are 800 to about 3,500 feet thick, and consist chiefly of fine- to coarse-grained clastic sediments that were deposited in shallow marine embayments. In places they include bentonite, tuff, and agglomerate. This section is known as the San Diego formation in southwestern California and mainly as the Salada formation in Baja California.

Nonmarine strata of Pliocene age are widely distributed in the interior parts of the province. Fluviatile and lacustrine conglomerate, arkosic sandstone, siltstone, and clay reach a maximum thickness of at least 10,000 feet along and near the western margin of the Coachella and Imperial Valleys (fig. 8), and in parts of this area they overlie a section of marine sandstones and siltstones as much as 4,000 feet thick (Dibblee, Contribution No. 2, this chapter). The marine strata, known as the Imperial formation, were deposited in a shallow embayment that extended northward from the Gulf of California during lower Pliocene time. They contain abundant marine fossils of tropical affinities (Durham, Contribution No. 4, Chapter III).

Locally preserved in the area west of the San Jacinto Mountains is as much as 7,000 feet of continental sandstones, siltstones, and conglomerates, some of which form typical redbed sequences. Known as the Mount Eden and San Timoteo formations (Frick, 1921, 1933; Fraser, 1931, pp. 511-514; Axelrod, 1937, 1950), these rocks have been dated as middle Pliocene and upper Pliocene, respectively, on the basis of plant and vertebrate fossils.

Quaternary Rocks. Marine sedimentation in many of the coastal areas appears to have been essentially continuous from late Pliocene into early Pleistocene time. The lower Pleistocene deposits, mainly sands, silts, and marls, generally grade inland into continental accumulations that correspond in age to fluviatile sediments laid down in isolated basins still farther inland.

Submergence and intermittent emergence of the coastal areas during later Pleistocene time led to development of extensive marine terraces (fig. 2), most of which are thinly veneered with marine sediments that in turn are largely concealed by terrestrial deposits. The well-known mid-Pleistocene orogeny of the southern California region is attested by marked unconformities between the marine cappings on some of the terraces and the underlying deformed strata of earlier Pleistocene age. These and other relations within the Pleistocene marine section have been studied with particular care in the San Pedro area (Arnold, 1903; Woodring, Bramlette, and Kew, 1946).

Fluviatile and lacustrine sedimentation during the Pleistocene epoch is recorded in many interior parts of the province by masses of coarse- to very fine-grained sediments, some of which have yielded vertebrate and plant fossils. These deposits include the Ocotillo conglomerate and Brawley formation of the Coachella and Imperial Valleys (Dibblee, Contribution No. 2, this chapter), the Bautista beds of the San Jacinto River Valley and nearby areas (Frick, 1921, pp. 283-288; Fraser, 1931, pp. 504-516, 536-537), the Temecula arkose of the Elsinore-Temecula Valley (Mann, 1951), and similar sediments in many parts of Baja California. Gravels and sands that are in part contemporaneous with these deposits, and also with some of the coastal marine terrace deposits, form many of the largest alluvial fans in the region (fig. 9). Some of these fossil fans have been partly buried by younger alluvial material, whereas others have been deeply trenched since Pleistocene time.

Widespread sediments of Recent age include marine and lagoonal deposits in the coastal areas, alluvial-fan and flood-plain sands and gravels in many of the valleys, lacustrine silts in the Imperial Valley area, swamp and pond deposits in cienegas of the mountain areas, and aeolian deposits that include prominent belts of dunes along the coast and along the western margins of the Imperial and Coachella Valleys.

Volcanic rocks of probable Quaternary age appear as remnants of flows in the Santa Ana and Santa Margarita Mountains, and are widespread in parts of Baja California (Beal, 1948, pp. 84-85; Anderson, 1950, pp. 46-47). Most are andesitic or basaltic in composition, and they occur typically as mesa cappings and as broad aprons of lava in some valleys. Volcanic cones are present along the east coast of Baja California, and some of them show evidence of Recent activity.

STRUCTURE

General Relations

In the broadest structural sense, the Peninsular Range province can be regarded as an uplifted and westward tilted plateau that has been broken into several large, subparallel blocks by major faults (fig. 3). Some of these blocks consist of rocks that lie both above and below the great Mesozoic unconformity, but most of them consist almost wholly of rocks that represent the older sequence. The major faults trend northwest, and many of the elongate blocks that they define are segmented by cross faults. Some of the blocks have undulatory profiles that may be in part ascribable to transverse warping.

Most of the major faults appear to have been intermittently active during large parts of Cenozoic time, and plainly have had a profound influence on the distribution, thickness, and lithology of the younger sedimentary rocks, as well as on the development of the various landforms. Adjacent fault blocks commonly have had distinctly different histories, which has complicated the problems of stratigraphic correlation and geomorphic interpretation in both onshore and offshore parts of the province.

Structural Features in the Older Rocks

The metamorphic rocks that antedate the southern California batholith, although much deformed in detail, have a remarkably consistent regional grain. In nearly all large areas of exposure they

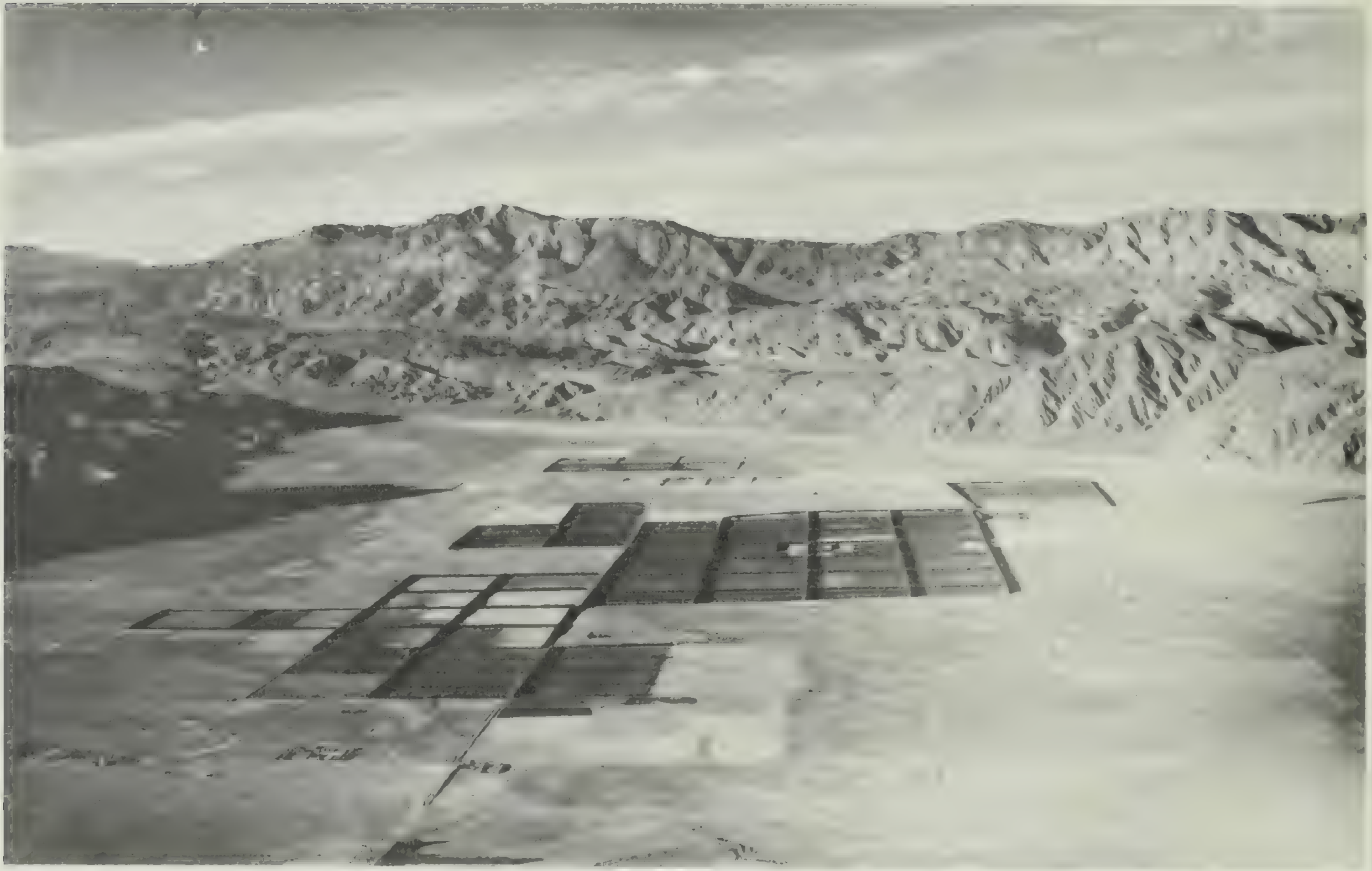

FIGURE 8. Aerial view north-northeastward across Borrego Valley toward the Santa Rosa Mountains, showing scarp of the San Jacinto fault at far edge of valley flat. Beyond this, at successively higher levels, are scarps associated with the Clark and Santa Rosa faults. The badlands at the northern corner of Borrego Valley, immediately beyond the shadow area, have been carved in terrestrial sedimentary rocks of Tertiary age. *Pacific Air Industries photo.*

trend northwest to north-northwest and dip steeply southwest or moderately to steeply northeast. Other trends, however, are common along or near many masses of plutonic rocks. The metamorphic terrane has been so extensively interrupted by igneous intrusives and so much divided into separate structural units by major faults that large-scale folds, if present, are difficult to recognize, and the section in most areas is best regarded as homoclinal. Large folds in the older rocks thus far have been traced only in parts of the Mesozoic section in northwestern Baja California.

Bedding commonly is recognizable in the rocks of sedimentary origin, and original flow structure is preserved in many of the metavolcanic rocks. Foliation and schistosity are broadly conformable with these primary features, but transect them in the axial parts of numerous small folds. Ptygmatic folds are locally abundant in the injection gneisses and other hybrid rocks.

Primary structural features of the plutonic rocks include mineralogic and textural layering, planar orientation of tabular minerals and inclusions, linear alignment of elongate minerals and mineral streaks or clots, and well-defined sets of joints. Most of these features are related systematically to the form—generally steep-walled and stock-like—of the individual intrusive masses in which they occur. The patterns of intersecting joints in some plutons of the southern California batholith are very distinct, especially as viewed from the air (fig. 6), and the exposed joint blocks commonly weather to boulders of distintegration (Larsen, 1948, pp. 114-117) that are prominent even on the more densely brush-covered slopes (fig. 7).

Younger joints, some more regional in their distribution and others apparently related to nearby major faults, also are present in the batholith rocks. Pervasive shearing along fault zones has converted both the igneous and metamorphic rocks into flaser gneisses and large, tabular masses of mylonite in several areas.

Major Faults

The fundamental elements of Cenozoic structure in the province are the steeply dipping major faults that slice the older rocks into northwest-trending blocks. Many of these breaks have remained active to the present time, and hence transect the younger rocks as well. The principal faults and fault zones in the northern part of the province are shown in plate 3, and include the Newport-Inglewood, Norwalk, Whittier, Chino, Elsinore, Agua Tibia-Earthquake Valley, Aguanga-Felipe, San Jacinto, Clark, and Santa Rosa. Similar fault zones are present in the offshore area, and the province is bounded on the north by the San Andreas fault and by east-trending faults that form parts of the Transverse Range pattern. To the south, in Baja California, the bold east faces of the Sierra Juarez and Sierra San Pedro Mártir are the scarps of a major fault zone, and other large faults lie beneath the waters of the Gulf of California.

Some of the faults are well-defined single breaks, especially where they cut rocks of Tertiary or Quaternary age. Most, however, are zones of subparallel to broadly anastomosing breaks that separate lenses and slices of profoundly shattered to almost undeformed rocks (fig. 10). These fault-bounded masses range from slivers a few feet thick to gigantic pinching-and-swelling slabs that are thousands of feet in maximum thickness (fig. 11). Several of the major fault zones show a ramifying pattern on a still larger scale, as in the area southwest of the San Jacinto and Santa Rosa Mountains.

The individual breaks commonly are difficult to recognize where they cut the younger sedimentary rocks, as on the floors of the Los Angeles basin and the valley between Elsinore and Temecula. Others, in contrast, are locally well exposed, and elsewhere are plainly marked by scarplets, sag ponds, offset drainage lines, or other features resulting from recent movement. Also observable along many of the faults are unusual trends in the distribution of vegetation, numerous springs disposed in a linear pattern, sharp differences in ground-water levels, and trenches, elongate ridges, anomalous scarps and benches, and other features characteristic of fault-controlled topography (figs. 4, 8, 9, 11).

Evidences of recent movement are especially well preserved along parts of the San Jacinto, Clark, and Earthquake Valley faults, but in general the most distinctive topographic evidences of faulting appear to have resulted wholly from erosion along the fault zones. Some segments of the major faults are concealed beneath very recent accumulations of alluvium and other debris; much of the trace of the Elsinore fault along the southwestern side of the Agua Tibia Mountains, for example, has been buried by large masses of slope wash and landslide material.

That displacements along several of the faults have been very large is demonstrated by the juxtaposition of dissimilar masses of older rocks and by measurable offsets in sections of the younger rocks, and is further suggested by the occurrence of large scarps, many of them parts of the present topography and others buried beneath thick sections of Cenozoic rocks in some of the basins. The Newport-Inglewood fault zone separates rocks that were wholly unlike when they were formed, and that have undergone dissimilar types of metamorphism (Woodford, et al., Contribution No. 5, this chapter). Although discontinuities of this fundamental type have not been demonstrated along the Elsinore, San Jacinto, and other fault zones to the east and southeast, individual plutons and other masses of crystalline rocks cannot be correlated across these breaks within specific small areas.

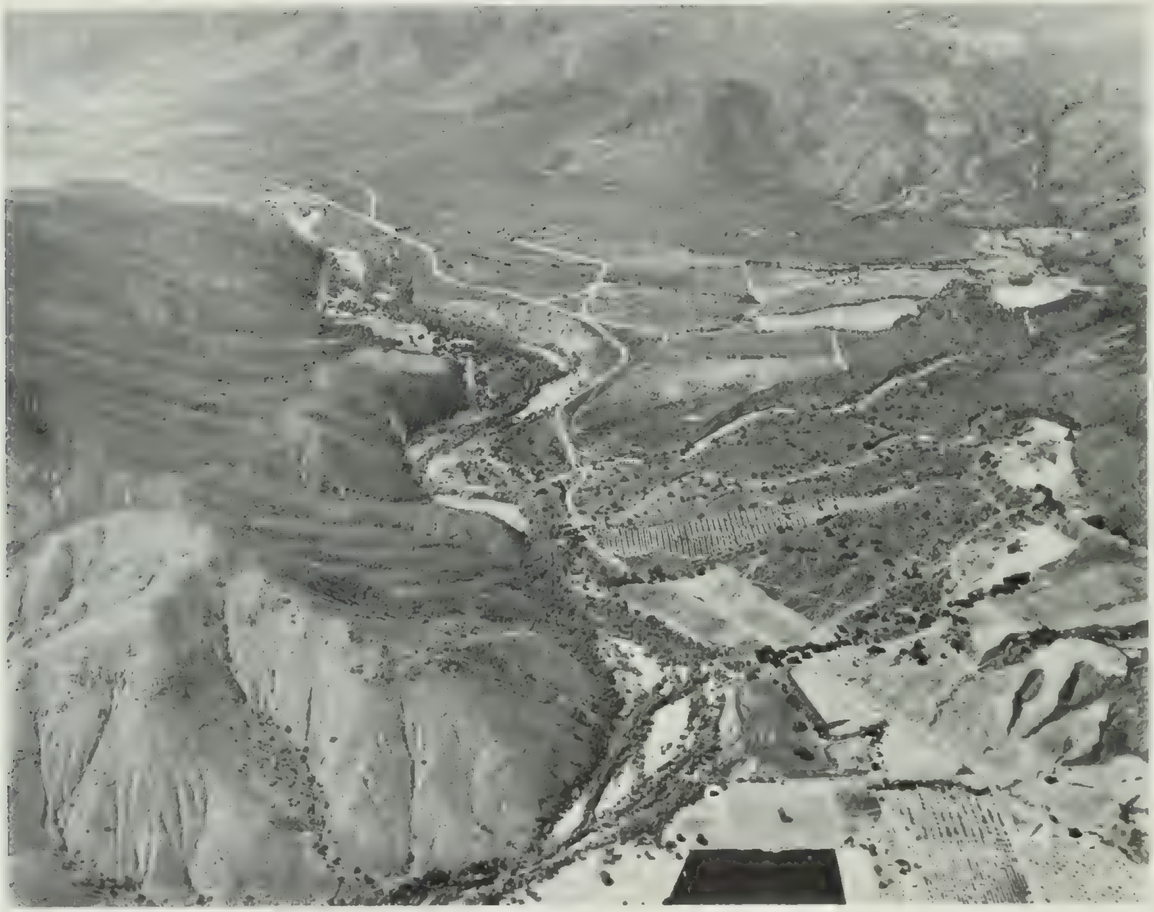

FIGURE 9. View northwestward over valley of the San Luis Rey River east of Pala, showing large alluvial fans of Pleistocene age. These consist of material derived from the Agua Tibia Mountains, which are off the view at right. Hills at left and in distance are underlain chiefly by gabbro; note the rib-like projections of pegmatite dikes on several of these hills. The broad bench at the upper right-hand corner of view marks the position of the Elsinore fault zone. *Pacific Air Industries photo.*

The direction of net slip along most of the major faults probably has been oblique, but not enough evidence is yet available precisely to determine this direction, the amount of the slip, or the degree to which reorientation of movement may have taken place during the history of a given fault. Large dip-slip displacements are suggested by vertical differences in the positions of corresponding rocks on opposite sides of some faults, but many of these relations might be as well explained in terms of dominantly strike-slip, or lateral, movements. Scarps in alluvium and other Quaternary deposits testify to a distinct vertical component of recent movements along the San Jacinto fault zone, and the graben-like structure of the Elsinore-Temecula Valley (fig. 10) seems best explained in terms of a large dip-slip component of movement along some faults in the Elsinore system. A somewhat similar narrow graben appears to be present on the floor of the Gulf of California between San Felipe and Santa Rosalia (fig. 1).

Topographic evidence of recent strike-slip (right-lateral) movement of the San Andreas type is widespread in the San Jacinto fault system, and is present locally in the Elsinore system, as well. Additional evidence appears in the form of offset fold axes, as well as drag folding and wrinkling, in adjacent sedimentary rocks of Cenozoic age, especially in areas along the western margin of the Imperial Valley. As pointed out by Dibblee (Contribution No. 2, this chapter), the series of east-trending drag folds and the numerous northeast-trending faults that are present in some of the major blocks between the Elsinore and San Jacinto fault zones may well be subsidiary features in a strain pattern resulting from a general northwest-southeast clockwise torsional stress. Large-scale strike-slip movements are suggested by the relative positions of several apparently related masses of older rocks on opposite sides of the major fault zones, but the evidence thus far obtained must be regarded as presumptive.

Some of the faults, like the Whittier, appear to have been active mainly during late Cenozoic time, but most of them evidently are parts of an extensive, deep-rooted system that probably was developed as long ago as late Mesozoic time. Where they cut strata of Cenozoic age, as in the Los Angeles basin, they displace these rocks less and less in progressively higher parts of the section, and locally they die out upward into zones of folding.

Structural Features in the Younger Rocks

The thick sections of sedimentary rocks in the major basins have been folded along axes that trend west-northwest to north-northwest. Most of the large folds are open, but their flanks are complicated in places by unconformities or by minor wrinkling. Their crests and troughs are undulatory, and several well-defined elongate domes along two major lines of anticlinal folding in the Los Angeles basin have been of particular significance in the accumulation of oil. Many of the folds in this basin have cores of older crystalline rocks that evidently were deformed along with the overlying sedimentary strata; some of these cores also may have been hills at the time when deposition of the younger sediments began.

Most of the folding in the Los Angeles basin appears to be genetically related to nearby faults, and some of it plainly has resulted from fault displacements at greater depths. As suggested by Ferguson and Willis (1924, pp. 579-581), the folds may be products of right-lateral movements between buried blocks of "basement" rocks; parts of these blocks, however, must also have been warped during the folding, as they are present as deformed cores in many anticlines. The Tertiary rocks along the margins of the Imperial and Coachella Valleys have been sharply folded where they lie adjacent to major faults, and "basement" rocks also have participated in much of this folding. Some of the largest folds in this area, however, are less directly related to faults. A typical example is the southeastward plunging anticline at the south end of the Santa Rosa Mountains, where the sedimentary strata are wrapped around a broad nose of much older crystalline rocks.

The Cenozoic rocks in the western part of Baja California occupy a broad and very gentle syncline whose axis trends northwest and in part lies offshore (Beal, 1948, pp. 91-92). A broad anticlinal uplift is present along the Gulf of California in the southeastern third of the peninsula. Both of these folds are complicated by many open to very tight folds of much smaller size, but no well-defined anticlines and domes like those that are associated with faults in the Los Angeles basin have been reported.

Episodes of deformation are recorded by numerous unconformities in the Cenozoic section, particularly in and near the Los Angeles basin. Paleocene deposits rest upon a surface that truncates tilted and locally folded strata of Upper Cretaceous age in the Santa Ana Mountains, and in areas farther south Eocene deposits lie upon what may be the same surface of low relief. Widespread erosion and local deposition characterized much of Oligocene and early Miocene time, and were interrupted in mid-Miocene time by large-scale faulting and uplift. Marked changes were made in the pattern of drainage and in the sizes and shapes of sedimentary basins, and the diastrophism is reflected by major unconformities that are especially prominent along the margins of the sedimentary basins. Smaller breaks in the section represent additional deformation in late Miocene and Pliocene time.

The mid-Pleistocene orogeny is demonstrated by major unconformities in the coastal areas, and in some of the nonmarine interior

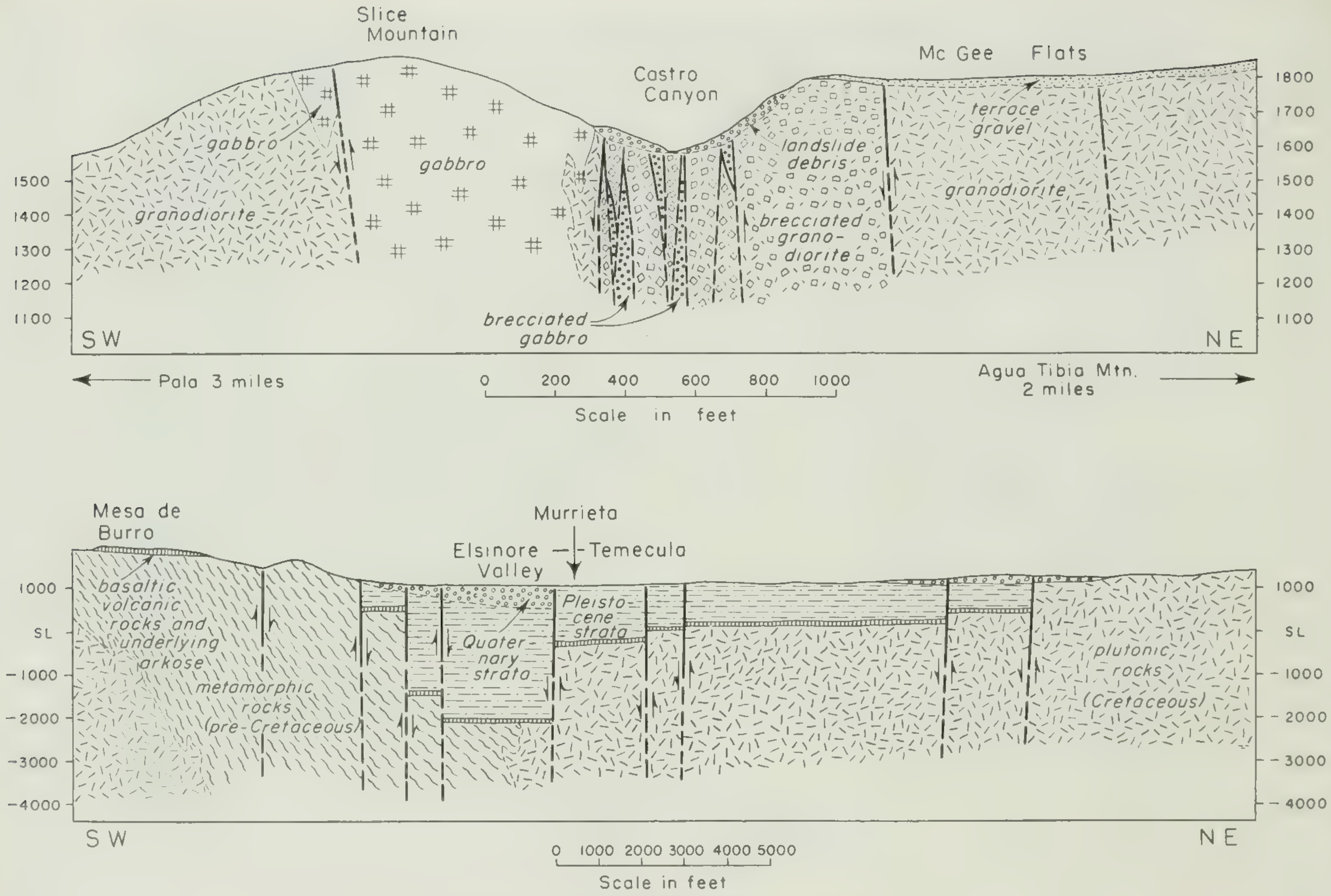

FIGURE 10. Sections across the Elsinore fault zone.

basins, as well. This episode of deformation evidently has continued to the present time, as suggested in many areas by recent warping and by recent displacements along faults. Continuing development of numerous anticlinal folds in the Los Angeles basin has led to remarkably faithful surface expression of their structure, and very young alluvium is involved in some of this folding.

GEOMORPHOLOGY

General Features of the Block Units

Many features of the present landscape in the Peninsular Range region were initially defined during the widespread mid-Pleistocene orogeny, and have been subsequently modified only in detail. Others, in contrast, may have been exhumed from beneath a protective cover of younger sedimentary rocks, and hence may be much older. Regardless of the details of their respective histories, all of these features are related in a fundamental way to the histories of fault-bounded blocks.

The form of the uplifted blocks has been developed in its present detail mainly by erosion, the effects of which have been controlled in many places by the lithology and structure of the rocks involved. In addition, transverse warping may have been responsible for broad differences of present topography within some blocks, as in the San Jacinto, Santa Rosa, and Agua Tibia Mountains. Deposition on the uplifted blocks during Quaternary time has been essentially restricted to local basins, some of which have been downwarped or downfaulted; to the larger canyons and valleys, where erosional terraces have been veneered with coarse sediments; and to the margins of the blocks, where aprons of alluvial material have accumulated.

The relatively depressed blocks are largely mantled by alluvial fill and local lacustrine deposits. Some also contain sections of older nonmarine deposits, and hence must have been lowland blocks in pre-Quaternary time. Others, like those that form the floor of the Los Angeles basin, were low enough to be covered by considerable thicknesses of marine strata whose lithology and structure reflect numerous episodes of deformation. Similar complications in the histories of blocks that now are high are suggested by local remnants of pre-Quaternary sedimentary strata that have been preserved on their surfaces.

Erosion Surfaces

Broad surfaces of low relief, interrupted here and there by hills and ridges, are present in many of the highland areas (fig. 11), and appear at altitudes ranging from 1,200 feet near the coast to 6,000 feet or more in the San Jacinto Mountains, Laguna Mountains, and parts of northern Baja California. They have been developed mainly on the pre-Cenozoic terrane of crystalline rocks, and are characterized by discontinuous but locally thick mantles of soil and weathered rock.

These surfaces have been interpreted as remnants of a single, once-extensive peneplain, commonly known as the southern California peneplain, by Fairbanks (1903), Dickerson (1914, pp. 259-260), Ellis and Lee (1919, pp. 37, 48-49), English (1926, p. 64), Miller (1935), Gale (1932, p. 2), and others. The positions of the surfaces at various levels have been attributed to dislocation of the peneplain by block faulting during Quaternary time. Sauer (1929), in contrast, has concluded that the typical surfaces of low relief were formed independently at different levels, and that each specifically reflects the history of the block on which it appears.

Some of the surfaces may be exhumed features that were originally formed in pre-Quaternary time, as suggested by Dudley (1936) and others, and hence they may be older than some nearby surfaces that lie at higher altitudes. Larsen (1948, pp. 12-13), however, has presented evidence against this argument in at least one large area. If truly exhumed, at least some of these older surfaces might be correlative with the surface exposed beneath Paleocene and Eocene rocks in areas nearer the coast.

Several of the surfaces may have been warped during Quaternary time. That many of them have been offset along faults seems probable, particularly in areas where the implied vertical displacements are compatible with displacements of nearby upper Tertiary and Quaternary rocks. On the other hand, it seems unwise to postulate faults solely on the basis of geomorphic evidence, in order to account for the discordance of presumedly correlative surfaces. Miller (1935), for example, has inferred an impressive mosaic of such faults for a large part of the province, but detailed mapping of the bedrock in several areas has convinced the writer that most of these faults do not exist. Everhart (1951, p. 97) has reached a similar conclusion on the basis of mapping in the Cuyamaca Peak quadrangle. It seems clear that the origin of the erosion surfaces cannot be established in advance of careful geologic mapping, structural analysis, and consideration of all factors that affect the erosion of the rock types involved. The work of Larsen (1948, pp. 5-15) constitutes a realistic approach to the problem.

Terraces

Terraces are present along many of the streams, and their number, extent, and elevations above present stream level vary from one block to another. They are younger than the erosion surfaces described above, but appear to be in part contemporaneous with some of the marine terraces along the coast.

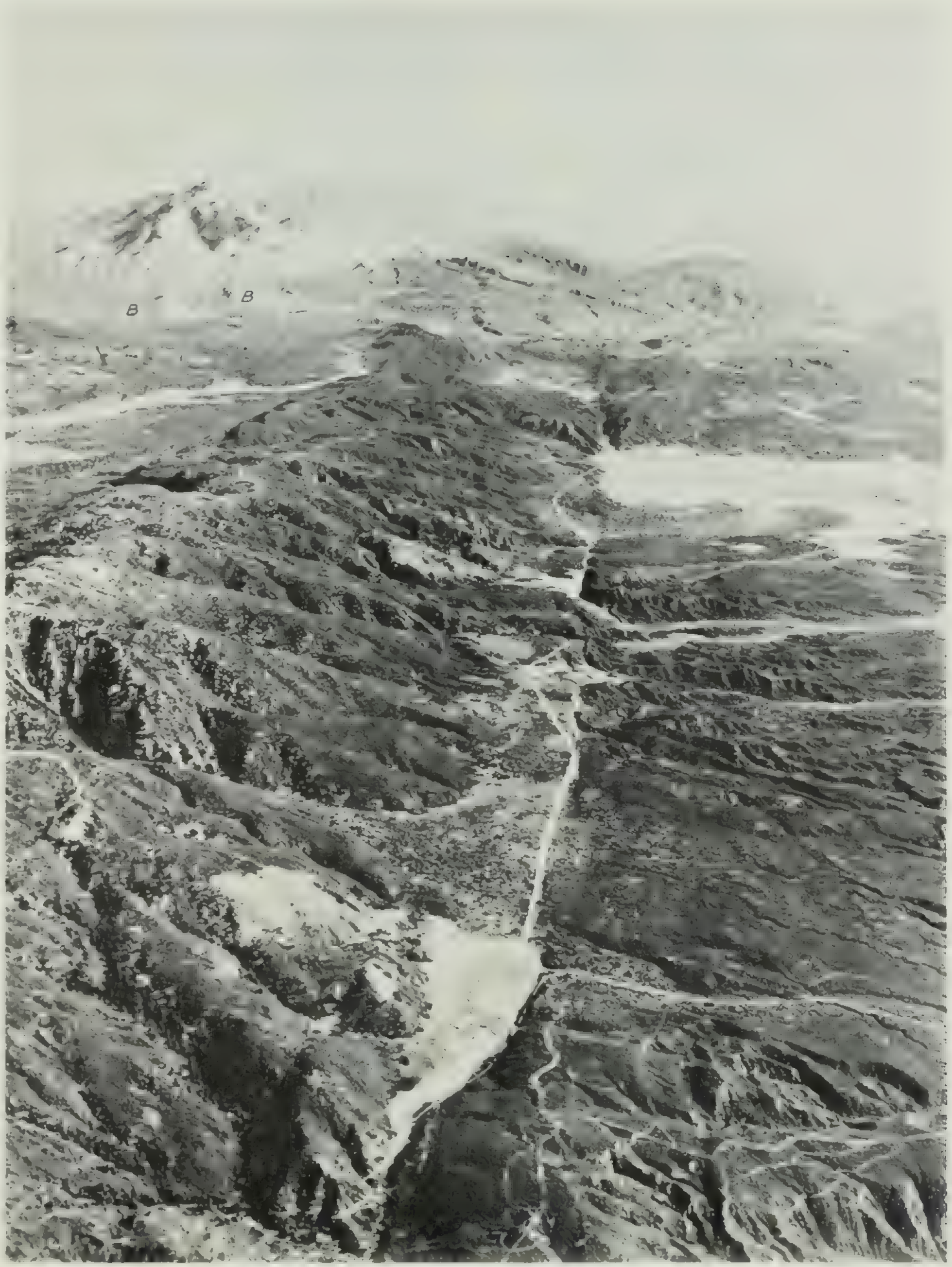

FIGURE 11. View southwestward along the San Jacinto fault zone toward the Santa Rosa Mountains. Note the broad trench and offset streams along the main break in central part of view, as well as the difference in altitude between Hemet Valley at left and the broad Anza surface at right. Recent alluvium and Pleistocene Bautista beds (B) appear in Hemet Valley; the remainder of the area is underlain by igneous and metamorphic rocks. Thomas Mountain is in foreground at left-hand edge of view, Toro Peak is in left distance, and Borrego Valley is in far distance at right. *Photo by J. S. Shelton and R. C. Frampton.*

As many as 13 to 22 marine terraces, some of them warped or otherwise deformed, are present along parts of the coast, and the highest ones are about 1,300 feet above sea level in southern California and nearly 2,000 feet above sea level in Baja California. They have been described by Ellis and Lee (1919, pp. 25-30), M. A. Hanna (1926, pp. 192-198), Woodring, Bramlette, and Kew (1946, pp. 113-118), Beal (1948, pp. 28-33), and many other investigators. They demonstrate considerable submergence of the coastal areas during late Pleistocene time, but present many problems of origin and correlation that remain to be solved.

Drainage Anomalies

Among the anomalous features of drainage in the region are convex stream profiles and abrupt changes in gradient that are not related to differences in the rocks traversed, unusual drainage patterns that feature numerous right-angle bends (fig. 6), hillside swamps and ponds, sag ponds and graben lakes, and offset streams (fig. 11). These are related mainly to the distribution and history of faulting, and have been discussed by Sauer (1929), Larsen (1948, pp. 5-15), and others. Evidence of stream capture is widespread, and capture of numerous other streams seems to be imminent.

Several streams that flow across the Los Angeles basin have cut downward through structural blocks that have risen during Quaternary time (see Woodford, et al., Contribution No. 5, this chapter). The Santa Ana River may well be similarly antecedent to the uplift of the Santa Ana Mountains, and San Felipe Creek probably is antecedent to two large uplifted ridges that are bounded by the Earthquake Valley and Felipe faults south of Borrego Valley. Many other streams whose courses lie athwart the trend of the major fault zones may also have cut downward through rising blocks, but in most instances this cannot be proved. Some anticlines in the Los Angeles basin evidently have risen so rapidly during late Quaternary time that none of the preexisting streams could breach them. On a much larger scale, rapid uplift of the Santa Ana Mountains along the Elsinore fault system evidently blocked the San Jacinto River from a former westerly course across the range, and diverted the drainage to northwest and southeast lines.

NATURAL RESOURCES

Soil, water, and petroleum are by far the most important natural resources in the California portion of the Peninsular Range province. The soil-water combination of course sustains the extensive agricultural development of the region, and irrigation in many areas imposes heavy demands on both surface-water and ground-water supplies. Domestic and industrial requirements also are very large, especially in the area centering about Los Angeles and in coastal areas to the south. The occurrence of water reflects, both directly and indirectly, the structural history of the region, particularly as it has governed the formation of ground-water basins. Many of the faults control the distribution of ground-water in detail, and numerous springs are present along some of these breaks.

Solar evaporation of sea water yields commercial salt and calcium chloride in the San Diego area, and iodine is recovered from oil-well brines in the Los Angeles area.

The Los Angeles basin contains enormous quantities of petroleum, chiefly in strata of Miocene and Pliocene age, and it is one of the major oil-producing areas of the United States. The occurrences of oil and gas in this basin are discussed in Chapter IX of this volume. Despite considerable search, areas elsewhere in the province have yielded no significant production of petroleum as yet, but there may well be hope for new discoveries in some areas (see, for example, Beal, 1948, pp. 120-133).

Rocks of Cenozoic age are of considerable economic importance in this region. Impressive quantities of sand and gravel, used mainly for construction purposes, are obtained from Quaternary deposits in the vicinity of Los Angeles, San Bernardino, San Diego, and other centers of population. Beds of late Tertiary and Quaternary age yield lesser amounts of brick clays, foundry sands, and non-swelling bentonite in several of these areas, and beach and dune deposits yield various sands for specialty uses. Commercial quantities of grinding pebbles, mainly metamorphosed volcanic rocks, have been obtained from several beaches between Oceanside and San Diego.

In the Corona-Elsinore area, strata of Paleocene age are worked for glass sand and high-grade fire clay (Sutherland, 1935), and once were worked sporadically for lignite and sub-bituminous coal of low grade. Similar strata yield china clay in the northern part of the Santa Ana Mountains.

Diatomite is mined on a large scale from upper Miocene marine beds in the Palos Verdes Hills (Woodring, Bramlette, and Kew, 1946, pp. 33-35, 119-120). The largest gypsum mine in the State has been developed in a bedded deposit of probable late Miocene age in the Fish Creek Mountains southeast of Borrego Valley (see Ver Planck, Contribution No. 1, Chapter VIII), and small amounts of gypsite have been mined near Corona. Celestite also has been obtained commercially from a deposit in the Fish Creek Mountains. Deposits of sulfur are present along the eastern margin of the province, especially in Baja California, where they commonly are associated with gypsum and appear to have been developed in part through fumarolic and solfataric action. Calcite of optical grade occurs as pockets and fissure fillings in Tertiary sandstone at several localities near the south end of the Santa Rosa Mountains.

Granitic and gabbroic rocks of the southern California batholith have been quarried for dimension stone, aggregate, or riprap in many places (Larsen, 1948, p. 129; Hoppin and Norman, 1950; MacKevett, 1951). Numerous bodies of pegmatite have yielded commercial quantities of feldspar, quartz, and gem minerals, and a few have been worked for lithium minerals, mica, radio-grade quartz, or other materials (see Jahns, Contribution No. 5, Chapter VII). Bodies of altered ultrabasic rocks have yielded small quantities of amphibole asbestos in the San Jacinto Mountains, and magnesite in an area south of Winchester (Hess, 1908; Gale, 1914).

Recrystallized limestone of pre-batholith age is quarried on a large scale in the Jurupa Mountains, northwest of Riverside, where it serves a major part of the Portland cement industry of southern California. Large reserves of limestone occur elsewhere in the region, especially in the Santa Rosa Mountains and along the northern margin of the San Jacinto Mountains. Metamorphosed volcanic and intrusive rocks are quarried for roofing granules near Corona, and altered volcanic rocks yield pyrophyllite in the costal area southwest of Escondido (Jahns and Lance, 1950).

Among the metals, gold has been economically the most important in the California portion of the province. A substantial aggregate production has been obtained, chiefly prior to 1910, from many small to moderately large vein deposits in the Julian district (Donnelly, 1935), the Perris area (Sampson, 1935), the Santa Ana Mountains (Fairbanks, 1893, pp. 114-117; Larsen, 1948, pp. 131-132), and other areas where crystalline rocks of pre-Cenozoic age are exposed. Some placer gold also has been won from Recent stream gravels and from patches of reddish, coarse, well-cemented gravels of probable Eocene age.

Associated with bodies of gabbroic rocks in the Julian district are massive sulfides that are moderately nickeliferous (Creasey, 1946), and smaller deposits of this type are present in the Santa Ana Mountains. Much mining has been done in scattered vein deposits of lead, zinc, and some copper that occur in the metamorphic rocks of the Santa Ana Mountains, and one lead-zinc deposit on Santa Catalina Island also has been worked commercially. Several tungsten deposits of contact-metamorphic origin have been worked in the Laguna Mountains and other areas in San Diego County. Of periodic interest but much less economic significance are the cassiterite-bearing quartz-tourmaline veins in the Temescal district southwest of Riverside (Sampson, 1935, pp. 515-518), molybdenite-bearing aplite dikes at several localities in Riverside and San Diego Counties, and numerous bodies of pegmatite that contain traces of uranium-, thorium-, and rare-earth-bearing minerals.

A summary description of ore deposits in Baja California recently has been provided by Wisser (1954), and need not be repeated here. The occurrences of principal interest are numerous gold-quartz veins of late Mesozoic age, and some placer accumulations derived from them; base-metal vein deposits of probable Tertiary age in the Sierra Victoria; manganese and copper deposits in sedimentary and volcanic rocks of Tertiary age along the Gulf of California (Touwaide, 1930; Wilson, 1948; Wilson and Veytia, 1949; Noble, 1950); and tungsten deposits of contact-metamorphic origin in the Sierra Juarez (Fries and Schmitter, 1945).

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4. GEOLOGY OF THE OCEANSIDE-SAN DIEGO COASTAL AREA, SOUTHERN CALIFORNIA

By Leo George Hertlein * and U. S. Grant †

INTRODUCTION

A brief summary of the stratigraphy, structure, and general geology of the Oceanside-San Diego coastal area, in the extreme southwestern part of California, is presented in this paper. Fundamentally, this area forms a segment of a narrow coastal plain, but many geologists have grouped it, for convenience, with the Peninsular Ranges, which adjoin it on the east. The geologic map (fig. 1) shows the southern part of the area discussed in the following paragraphs.

The visitor familiar with the geology and physiography of the Los Angeles region will at once notice four striking features that distinguish the Oceanside-San Diego area. These are (1) the mesaland topography (fig. 2), (2) the thin sedimentary cover that lies upon older "basement" rocks, (3) the complete absence of Oligocene and Miocene sediments, and (4) the comparatively slight structural deformation of beds that are Upper Cretaceous or younger.

The writers have studied the southern part of the present area in considerable detail and the results of these investigations were published in 1944. On the other hand, their investigations of the Oceanside district to the north have been of a reconnaissance nature, and the excellent papers of Hanna (1926, 1927) have provided most of the detailed data for this part of the area.

PHYSIOGRAPHY

The land surface of the Oceanside-San Diego area represents, in the main, a series of marine wave-cut terraces that have been carved into gently dipping conglomerates, sandstones, siltstones, and shales of Cretaceous, Eocene, and Pliocene age. These terraces can be summarized as follows:

Chiefly north of the San Diego River

Terrace	*Elevation above sea level*
Poway terrace	900-1,200 ft.
Linda Vista terrace	300-500 ft.
La Jolla terrace	25-200 ft.

Chiefly south of the San Diego River

Terrace	*Elevation above sea level*
Otay terrace	430-525 ft.
Sub-Otay terrace	425 ft. (approx.)
Avondale terrace	200-250 ft.
Chula Vista terrace	100-130 ft.
Nestor terrace	25-100 ft.
Tijuana terrace	20-50 ft.
Modern coastal flats	0-20 ft.

In the southern part of the area, the terraces increase in altitude as the Mexican boundary is approached. The lower terraces rise slightly as the La Jolla-Soledad Mountain block is approached from the south, and the Linda Vista terrace is poorly developed or is not recognizable on portions of Soledad Mountain (fig. 1).

The Poway, or highest broad terrace, is now eroded away over much of its former extent, but it is typically developed and well preserved in the area between Cowles Mountain and Twin Peak. It was cut on pre-Tertiary igneous and metamorphic rocks east of the area discussed in the present report. This terrace may have been developed during Pliocene time. Traces of other terraces at points as high as 1,300 feet were recorded by Hanna (1926) from Cowles Mountain. In the Peninsular Ranges farther east, the physiographic relations suggest that an old-age land surface with numerous monadnocks was rejuvenated in late Cenozoic time.

The Linda Vista terrace, 300 to 500 feet in altitude (fig. 3), was recognized by Ellis and Lee (1919). It was reported to extend from Poway Mesa to Soledad Mountain, and to represent a northern extension of the Otay terrace that is so well developed in the southern portion of this area. Likewise, the La Jolla terrace, which is 25 to 200 feet in altitude and is well developed at and south of La Jolla (fig. 4), perhaps may correspond to the Chula Vista terrace south of San Diego. Remnants of ancient beach ridges and abundant small, reddish-brown cemented sand concretions are interesting features on the Linda Vista terrace.

Several flat-bottomed, alluvium-filled valleys in this region are important agricultural assets. Among the larger of these are Poway Valley and El Cajon Valley, which lie at altitudes of 400 to 600 feet. The streams draining these valleys are entrenched as a result of uplift. According to Hanna (1926), these valleys resulted from erosion along the contact between old rocks and conglomerates that underlie the Poway terrace.

An interesting feature of the Otay terrace surface is the occurrence there of prairie mounds. These mounds may have been formed as a result of an earlier plant cover, combined with effects of deflation and deposition by the wind. Their origin was discussed by the present authors in 1944.

The Silver Strand along the southwest side of San Diego Bay, and Mission Beach along the west side of Mission Bay (False Bay), are shoreline accumulations of materials that have been brought to

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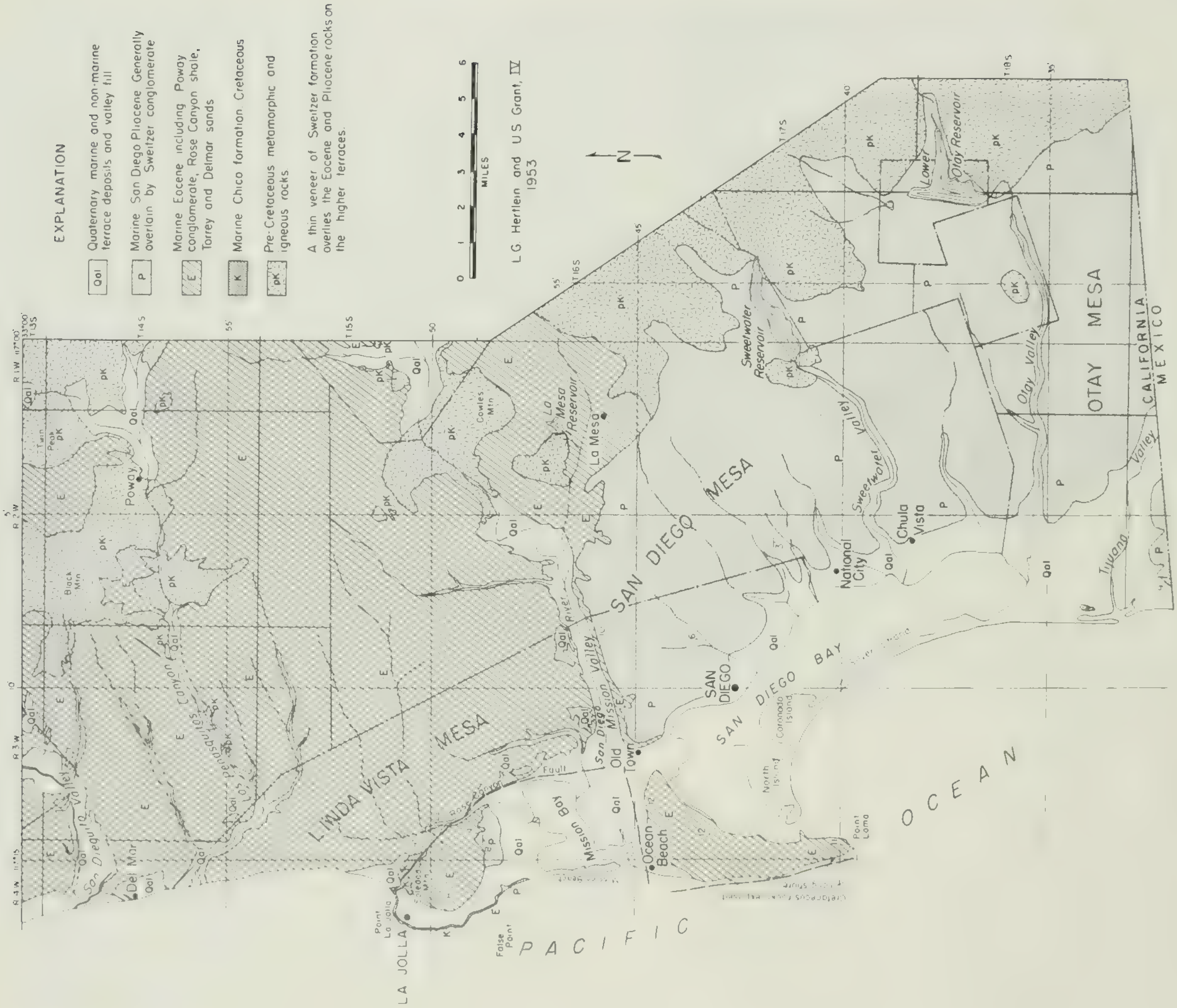

FIGURE 1. Geologic map of a part of the Oceanside—San Diego coastal area, southern California.

the coast by streams and then were shifted along the shore by currents and waves. Bay Point (Crown Point) may have been built in a manner similar to that of the Mission Beach sand spit, or perhaps it represents the wave-built portion of the La Jolla terrace.

Rainfall in this region is light, averaging only about 10 inches annually, and it occurs chiefly between October and April. The drainage is all westward. The San Dieguito River and Soledad Creek, in the northern portion of the area, reach the ocean through partly submerged valleys. The largest stream, the San Diego River, now empties into Mission Bay, but during earlier times it occasionally flowed into San Diego Bay. Its deltaic deposits form the lowland between Point Loma and Old Town (fig. 1). Smaller, intermittent streams flow in Sweetwater Valley, Otay Valley, Tijuana Valley, and other minor valleys. All these streams are practically at grade in the mesa lands area.

The presence of lagoons and low, marshy deltas at the mouths of streams such as the San Dieguito River is evidence of rather recent subsidence in the northern part of the area under discussion. Construction of dams and establishment of reservoirs on the major streams have reduced flow in their lower courses to comparatively small amounts except during years of exceptional precipitation, but there is much historic evidence of former great floods.

PRE-TERTIARY IGNEOUS AND METAMORPHIC ROCKS

The oldest rocks in this area are the Black Mountain volcanics and metamorphics (also known as the Santiago Peak series), which are exposed in the foothills east of the Tertiary sedimentary belt. This series consists mainly of dark-colored intrusive and effusive rocks of basic and intermediate composition, and includes andesitic and trachytic flows, agglomerates, tuffs, and metamorphosed conglomerates, sandstones, and shales. Quartzite and fissile shales are present in the eastern portion of the La Jolla quadrangle. The Cretaceous and younger sediments were deposited upon a ''basement'' of these older rocks.

The Black Mountain volcanic and metasedimentary rocks have been intruded by plutonic rocks such as quartz diorite and biotite granite. These may be parts of the southern California batholith, and hence may be of Cretaceous age. They are plainly older than the Cretaceous sedimentary rocks in the area, however. Roof pendants of the older rocks occur within the intrusives at various localities.

No fossils have been found in the Black Mountain series, but similar rocks in the Santa Ana Mountains to the north are underlain by fossiliferous rocks that are believed to be of Triassic age. These old rocks are very resistant to erosion, and commonly stand out as peaks and ridges in the eastern parts of the area. Hanna reports the thickness of the Black Mountain series to be more than 2,000 feet. Estimates of thickness must be approximate, as the attitude of layering and foliation in these rocks varies considerably from place to place. The structure is even less discernible to the south. Sweetwater Dam, about 10 miles east of San Diego, and Hodges Dam, on the San Dieguito River, are located on these rocks.

The quartz diorite is well exposed in the higher areas east of Black Mountains, as well as east of La Mesa at Grossmont. This rock contains about 40 percent quartz and 20 percent biotite, and most of the remainder is sodic plagioclase. Pegmatite and aplite dikes extend from the masses of quartz diorite into older rocks that flank these masses.

Gabbro is exposed in three small areas within the La Jolla quadrangle. The largest of these is west of Black Mountain. A smaller one, involving more basic gabbro, lies at the eastern end of the south branch of Poway Valley, near the eastern margin of the La Jolla quadrangle. The third area also is small, and lies near the head of Shepherd Canyon, in the east-central part of the quadrangle. Hanna (1926) identified the rock in this area as a gabbro or basic diorite. Some specimens contain 50 to 60 percent of oligoclase-andesine feldspar. Quartz is absent from parts of the rock, but in other parts, it is present to the extent of as much as 10 percent. The contact between the gabbro and the quartz diorite has not been observed, but Hanna (1926) believed the gabbro to be younger than the diorite.

A basalt dike 2 feet to 30 feet wide cuts Eocene rocks along the seashore about ½ mile north of Scripps Institution of Oceanography. A greenstone dike has been reported from an area along the southeast side of Point Loma, where it apparently intrudes Cretaceous rocks.

SEDIMENTARY ROCKS

Unmetamorphosed Cretaceous, Eocene, Pliocene, and Pleistocene sedimentary rocks form a section whose estimated maximum thickness is less than 4,000 feet. All these rocks were deposited in comparatively shallow water, and for the most part have experienced but slight deformation. They are chiefly sandstones, siltstones, and shales; minor amounts of conglomerate also are present. A columnar section of these rocks is presented in figure 5.

Cretaceous Rocks. Cretaceous sedimentary rocks are exposed only in narrow zones along the west shore of Point Loma and along the shore farther north, in the vicinity of La Jolla (figs. 1, 4); in the core of an anticline on Soledad Mountain (fig. 6); and in an area, perhaps 2 or 3 square miles in extent, that lies about 5 miles southeast of Carlsbad. The maximum thickness of this section is unknown, but it is believed to be about 500 feet at most localities. These rocks apparently lie upon the eroded surface of the Black Mountain series.

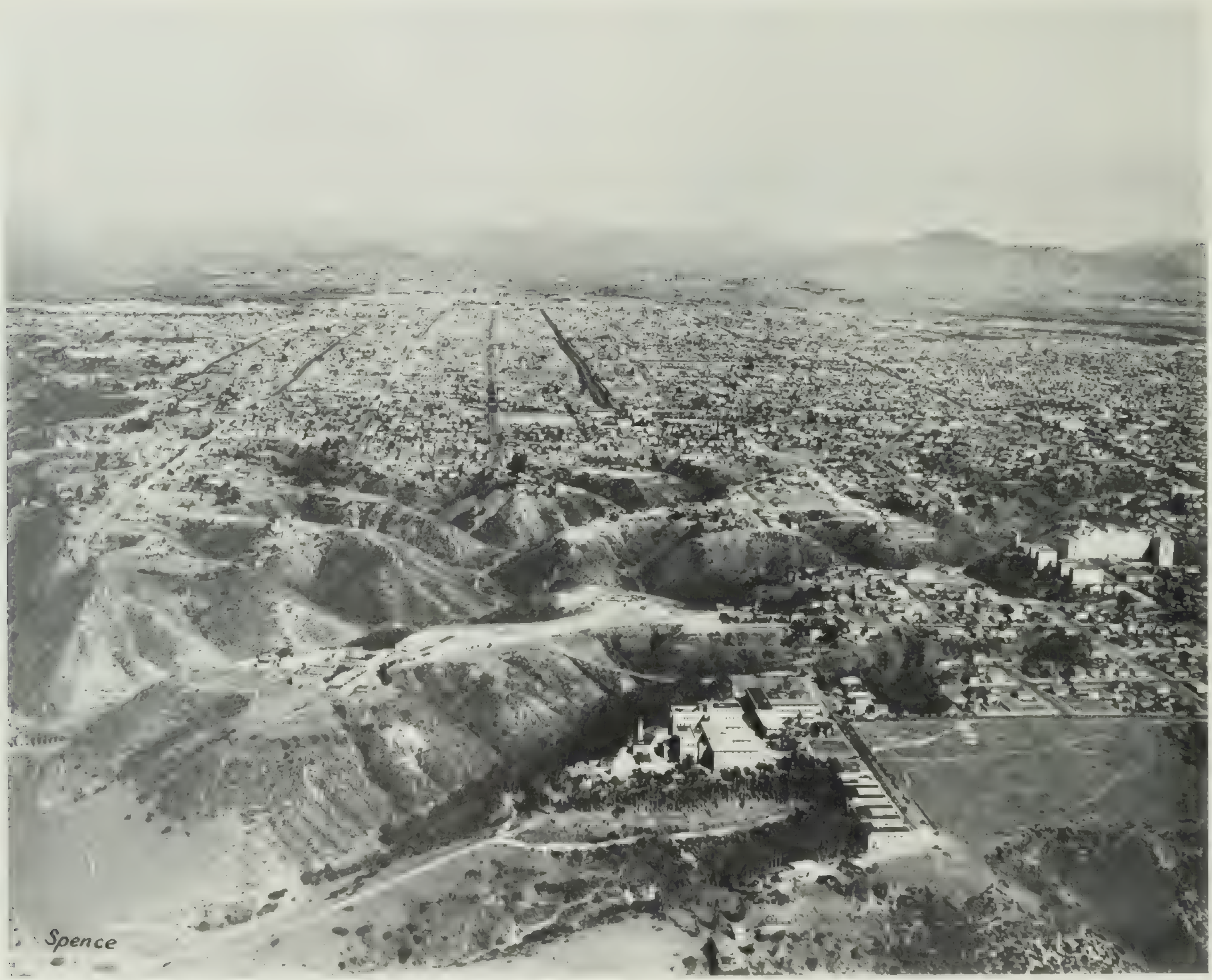

FIGURE 2. Air view eastward over San Diego Mesa from a point above south side of Mission Valley. Note the steep-sided, V-shaped young tributaries of Mission Valley, the flat-topped mesa, and the Peninsular Ranges of crystalline rocks in the distance. The obscure Eocene-Pliocene contact is exposed on the canyon slopes. *Air Photo by Spence, February 21, 1931.*

However, at a locality about 6 miles south of San Diego, a drilled well penetrated 269 feet of "red beds" that are above the Black Mountain series and below the marine sedimentary rocks of Cretaceous age. These "red beds" have been referred to the Trabuco formation of the Santa Ana Mountains where beds of similar lithology are believed to be of nonmarine origin.

The marine Cretaceous rocks are massive to well bedded, brown to gray, well cemented sandstones and fine-bedded shales that are in part carbonaceous and locally are concretionary (fig. 4). In these sediments are such fossil Foraminifera and mollusks as *Guadryina oxycona* Reuss, *Globotruncana obtusa* Cushman, *Acila demessa* Finlay, *Coralliochama orcutti* White, *Neomodon vancouverensis* Whiteaves, *Oligoptycha obliqua* Gabb, *Baculites fairbanksi* Anderson, *Hamites vancouverensis* Meek, and *Parapachydiscus catarinae* Hanna & Anderson, which indicate Campanian, upper Senonian, Upper Cretaceous age. *Coralliochama orcutti* White was collected by Frank Stephens and others from Cretaceous sediments, about 100 feet thick, that are exposed southeast of Carlsbad. There shale with some thin layers of sandy limestone are present over an area of about 2 or 3 square miles, where they dip about 3° NW and lie unconformably upon crystalline "basement" rocks. Foraminifera from those rocks have been described by Bandy (1951). A characteristic Campanian, Upper Cretaceous foraminifer, *Globotruncana arca* Cushman, is reported to occur abundantly in the faunal assemblage.

Beds containing a Cretaceous fauna similar to that of the San Diego region occur at Gualala, middle California, in the Coalinga district, and at Todos Santos Bay, in Baja California, Mexico. On Point Loma, the carbonaceous character of these beds once led to the sinking of a shaft in search for coal, and some deposits of coal were reported many years ago from points near Del Mar.

Eocene Rocks. Eocene rocks are represented in this area by the La Jolla formation and Poway conglomerate, whose combined thickness is about 1,575 feet. These rocks are believed to be middle Eocene or early upper Eocene in age.

The La Jolla formation is made up of three members. The lowest, which lies unconformably upon Cretaceous beds, is the Delmar sand, 100 feet in thickness. It occurs only along the coast north of La Jolla, and is well exposed in the sea cliffs and near the town of Del Mar (fig. 3). It is composed of greenish, gray, purple, and reddish sands and sandy shale. Some beds contain fossil mollusks such as *Ostrea idriaensis* Gabb, *Potamides carbonicola* Cooper, and *Unio? torreyensis* M. A. Hanna, which suggests that they were deposited in shallow brackish water. The Delmar sandstone may correspond to some portion of the Capay formation.

The Torrey sand, 20 feet to 200 feet in thickness, conformably overlies the Delmar sand in some places, and lies directly upon the Black Mountain volcanics in others. This unit is well exposed in the bluffs along the Torrey Pines grade (fig. 3), and it can be seen as erosional remnants high on the hillsides in the general vicinity of the mouth of Soledad Canyon south of Del Mar. The beds are composed of coarse-grained sand that commonly is cross-bedded, and are white or locally reddish in coloration. Marine fossils have been found in them, almost all the species of which also occur in the overlying Rose Canyon shale. It seems quite possible that the Torrey sand reflects approximately the same type of geologic events as those suggested by the Eocene Ione formation in the foothills of the Sierra Nevada, farther north in the State. It probably was deposited in a lagoonal and near-shore environment during a period of humid, semi-tropical climate.

The Rose Canyon shale, 300 feet thick, lies conformably upon the Torrey sand over much of the La Jolla quadrangle. In places it rests directly upon the Black Mountain volcanics, or upon Cretaceous sedimentary rocks. It is composed mainly of gray to brownish shales and silty mudstones, with minor amounts of conglomerate and a few thin beds of poorly stratified limestone. It contains characteristic marine Eocene fossils such as *Discocyclina cloptoni* Vaughan, *Flabellum sandiegoensis* M. A. Hanna, *Acila decisa* Conrad, *Crassatellites semidentata* Cooper, *Pelecyora aequilateralis* Gabb, *Turritella applini* M. A. Hanna, and *Aturia myrli* M. A. Hanna. These fossils indicate upper Eocene, approximately Domengine age.

The Rose Canyon beds are covered by Pliocene strata south of San Diego, but they have been encountered in many wells in the southern part of the area and hence may have a fairly extensive distribution. An analysis of the mineral content of Rose Canyon shale underlying the Pliocene beds on the south side of Mission Valley suggests, according to G. A. MacDonald, that the climate at the time of deposition favored pronounced chemical weathering. This evidence of warm, humid conditions is substantiated by the fossil mollusks, which represent forms whose living relatives are warm-water forms.

Poway Conglomerate. The Poway conglomerate, about 1,000 feet in thickness, overlies the La Jolla formation, in places conformably and in others unconformably. It appears to be mostly of nonmarine origin, and is composed largely of rounded pebbles and boulders as much as 3 feet in diameter. Andesitic boulders are most abundant. This conglomerate can be seen high on the sides of canyons east of Soledad Mountain. Lenses of sandstone within the conglomerate have yielded fossil marine Foraminifera and mollusks including *Brachidontes ornatus* Gabb, *Cardium brewerii* Gabb, *Crassatellites*

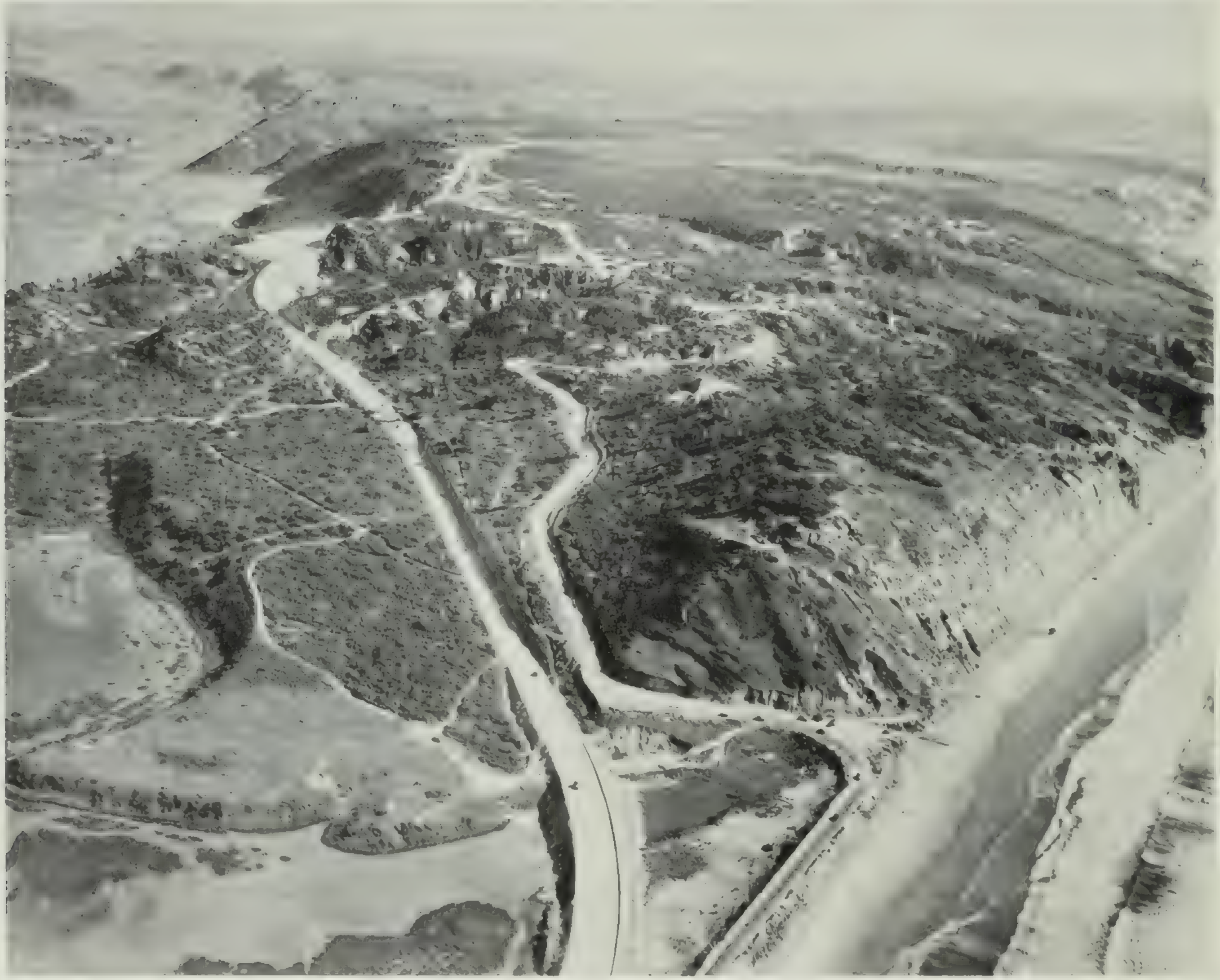

FIGURE 3. Air view southeastward from mouth of San Dieguito Valley, showing the Linda Vista Mesa, a northern extension of the San Diego Mesa; the type locality of the white, quartzose Eocene Torrey sand near the top of the highway grade; and a partial exposure of the Eocene Delmar siltstone and sandstone in the lower part of the near end of the beach cliff. *Fairchild Aerial Surveys photo, 1932.*

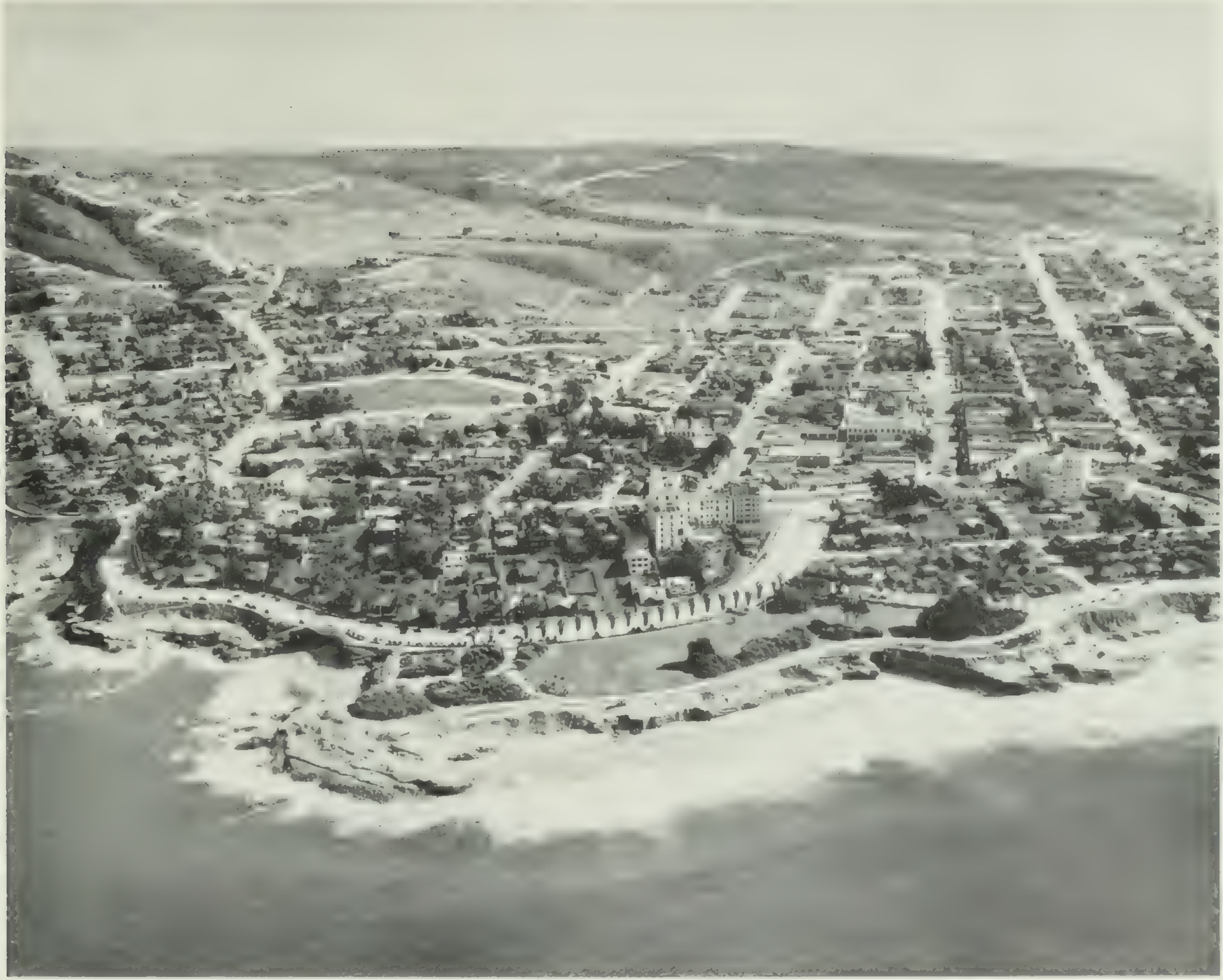

FIGURE 4. Air view southeastward toward La Jolla. Most of the buildings are on La Jolla terrace. A lower terrace lies between the broadly curving street and the shore, and a much higher, partially dissected and subdued terrace is present on the south flank of Soledad Mountain in the distance. The rocks along the shore are hard, concretionary sandstone of Cretaceous age. *Fairchild Aerial Surveys photo, 1932.*

mulates M. A. Hanna, *Ostrea idriaensis* Gabb, *Pitar uvasanus* Conrad, *Pteria* cf. *P. pellucida* Gabb, *Tellina tehachapi* Anderson & Hanna, *Conus remondii* Gabb, *Ficopsis remondii* Gabb, *Pseudoliva volutaeformis* Gabb, and *Turritella applini* M. A. Hanna. This assemblage of fossils is in general comparable to that of the upper Eocene type Tejon beds in Kern County to the north. Some vertebrate fossils also have been recovered from the Poway conglomerate; these, too, indicate on upper Eocene age.

Absence of Oligocene and Miocene Rocks. Oligocene sediments are lacking in this region, so far as is known; indeed, no sediments appear to represent the interval between Eocene and Pliocene. Recently, however, Emery et al. (1952, p. 523) have recorded the presence of Foraminifera in shaly beds that are interlayered with volcanic rocks on South Island, one of the Coronados Islands group, in Mexican waters just south of the international boundary. These Foraminifera are thought to represent a middle Miocene age. The associated volcanic rocks have been referred to the San Onofre breccia (see Woodford et al., Contribution 5, this chapter).

Pliocene Rocks. Pliocene fossils were identified by Dall in 1874 from beds in a water well dug in Cabrillo Canyon, Balboa Park, San Diego. These beds are a part of the San Diego formation, which is about 1,250 feet thick and is composed chiefly of yellowish and gray sandstone and siltstone, with minor amounts of conglomerate. This Pliocene formation lies with slight angular discordance upon the Rose Canyon shale, or, in places, on the Poway conglomerate or Black Mountain volcanics. It is well exposed at Pacific Beach, where it overlies Eocene beds and is overlain by Pleistocene sand, and is widely exposed in canyon and valley slopes in the San Diego Mesa. It is not known to occur north of the south slope of Soledad Mountain.

The San Diego formation contains typical invertebrate fossil echinoids and mollusks of middle Pliocene or early upper Pliocene age. Among these are *Dendraster ashleyi* Arnold, *Dendraster ashleyi ynezensis* Kew, *Lovenia hemphilli* Israelsky, *Merriamaster pacificus* Kew, *Arca trilineata* Conrad, *Ostrea erici* Hertlein, *Ostrea vespertina* Conrad, *Pecten bellus* Conrad, *Pecten (Lyropecten) cerrosensis* Gabb, *Pecten (Patinopecten) healeyi* Arnold, *Pecten (Swiftopecten) parmeleei* Dall, *Pecten (Pecten) stearnsii* Dall, *Pecten (Plagioctenium) subdolus* Hertlein, *Opalia anomala* Stearns, and *Opalia varicostata* Stearns. Beds containing many of the same species occur in the Santa Maria district, California, and at Cedros Island and Turtle Bay, Baja California. The fauna suggests water warmer than that now encountered in the San Diego region, and probably more like the present water in the vicinity of Cedros Island, Baja California.

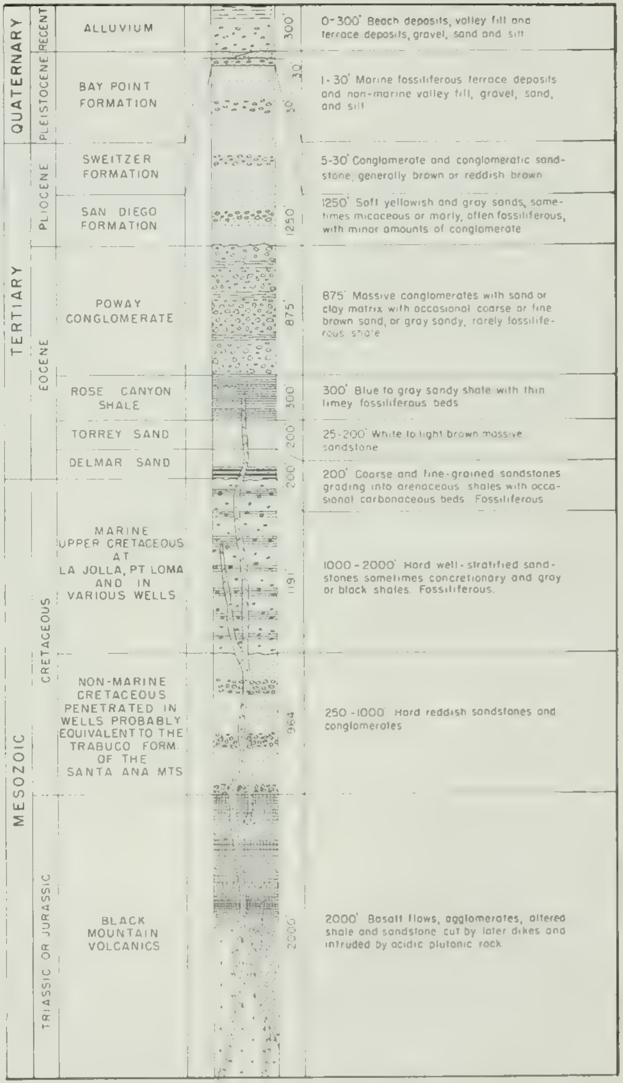
QUATERNARY
RECENT
ALLUVIUM
300'
0-300' Beach deposits, valley fill and terrace deposits, gravel, sand and silt
PLEISTOCENE
BAY POINT FORMATION
30'
1-30' Marine fossiliferous terrace deposits and non-marine valley fill, gravel, sand, and silt
TERTIARY
PLIOCENE
SWEITZER FORMATION
5-30' Conglomerate and conglomeratic sandstone, generally brown or reddish brown
SAN DIEGO FORMATION
1250'
1250' Soft yellowish and gray sands, sometimes micaceous or marly, often fossiliferous, with minor amounts of conglomerate
EOCENE
POWAY CONGLOMERATE
875'
875' Massive conglomerates with sand or clay matrix with occasional coarse or fine brown sand, or gray sandy, rarely fossiliferous shale
ROSE CANYON SHALE
300'
300' Blue to gray sandy shale with thin limey fossiliferous beds
TORREY SAND
200'
25-200' White to light brown massive sandstone
DELMAR SAND
200'
200' Coarse and fine-grained sandstones grading into arenaceous shales with occasional carbonaceous beds. Fossiliferous
MESOZOIC
CRETACEOUS
MARINE UPPER CRETACEOUS AT LA JOLLA, PT LOMA AND IN VARIOUS WELLS
1191'
1000-2000' Hard well-stratified sandstones sometimes concretionary and gray or black shales. Fossiliferous.
NON-MARINE CRETACEOUS PENETRATED IN WELLS PROBABLY EQUIVALENT TO THE TRABUCO FORM. OF THE SANTA ANA MTS
964'
250-1000' Hard reddish sandstones and conglomerates
TRIASSIC OR JURASSIC
BLACK MOUNTAIN VOLCANICS
2000'
2000' Basalt flows, agglomerates, altered shale and sandstone cut by later dikes and intruded by acidic plutonic rock

FIGURE 5. Columnar section of the rocks in southwestern San Diego County, as developed mainly from surface outcrops. Only the uppermost part of the Cretaceous section is exposed; the remainder has been encountered in various wells.

On the Sixth Avenue grade near Mercy Hospital, on the south side of Mission Valley, the Pliocene beds lie upon the Eocene Rose Canyon shale (fig. 2). Casts of *Trophosycon* have been found in the Pliocene beds at this place. Here the beds dip south about 10°; the dip, however, varies greatly from place to place, and only a short distance to the south the dip decreases and the beds are nearly horizontal.

The Pliocene rocks are mostly light brown, buff, or bluish gray, fine-grained sandstone, but local lenses of pebbles are present. A conglomerate that is more than 100 feet thick is exposed west of Tijuana. This and some other conglomerates apparently were deposited by rivers that drained the high mountainous areas to the east. Marly beds occur here and there on top of San Diego Mesa, chiefly near its eastern limits. Some cross-bedding, several lenses of conglomerate, and the absence of shale all suggest shallow-water deposition, possibly from low tide to a depth of 50 fathoms. The mineral grains are much fresher and less weathered than those in the Eocene rocks, possibly indicating a less warm and less humid climate.

Thin beds of bentonite occur on the sides of the mesa in Otay and Las Chollas Valleys, and in a shaft sunk near the Natural History Museum in Balboa Park, San Diego. These represent the only evidence of volcanic activity in this area during the Pliocene epoch, but volcanic rocks of probable Pliocene age are widely distributed in areas only a few miles south of the Mexican boundary.

Samples of sediments dredged from the sea floor off San Diego are lithologically similar to the San Diego formation and to the overlying Sweitzer beds. These have been described by Emery, et al. (1952, p. 525). Possibly a Pliocene wedge of shallow-water sediments extends for some distance west of the present shoreline.

Sweitzer Formation. The San Diego formation is unconformably overlain by a stratum of reddish-brown conglomerate and pebbly sandstone about 20 feet in maximum thickness. This is known as the Sweitzer formation. It can be seen capping most of the mesas south of Mission Valley, and a similar formation on the mesa north of Mission Valley may be a correlative. At places it continues as a blanket over the edges of the Otay terrace (mesa top) to lower terraces. No fossils have been found in these beds, which may be of late Pliocene or early Pleistocene age. The general mineral content is similar to that of the San Diego formation, and indicates that the rate of erosion in the source area was rapid in comparison to the rate of weathering of the mineral particles.

Pleistocene Deposits. Marine fossiliferous Pleistocene deposits occur as terrace material at many localities along the coast, and are especially well developed near San Diego, at Pacific Beach, and in Mission Bay at the west side of Bay Point or Crown Point. Excellent exposures once were available at the foot of Twenty Sixth Street in San Diego, as well as on the west side of Spanish Bight, but most of these are now covered.

The Pleistocene deposits are thin and have a maximum known thickness of 30 feet. They contain marine fossils, some of which are warm-water species not now living north of Scammon Lagoon, Baja California. The list of warm-water species includes *Cardium procerum*, *Chione gnidia*, *Dosinia ponderosa*, and *Turritella gonostoma broderipiana*. A terrace deposit on the west side of Point Loma contains species now living in the same region. It apparently is younger than the terrace beds at Pacific Beach and Mission Bay. Other similar terraces are present at low altitudes at numerous localities along the coast.

Some of the non-fossiliferous terrace cover and deeper valley fill may be Pleistocene in age. Recent alluvium occurs in most of the valley bottoms, delta flats, and bay flats.

STRUCTURE

There has been but little folding in the rocks of post-Black Mountain age. This may be due to the thin cover of sediments overlying the Black Mountain volcanics and metamorphics, and the crystalline rocks that intrude them. In this area the entire Cretaceous and Tertiary section is less than a mile thick, whereas more than 5 miles of sedimentary cover is present in the Ventura basin and the San Joaquin Valley.

The only major fold in the Oceanside-San Diego area is the asymmetrical anticline about a quarter of a mile northeast of the summit of Soledad Mountain (fig. 6). It trends northwest, and has a nearly vertical north limb and a gently dipping south limb. This fold appears to grade into a fault along Rose Canyon, where the beds near the Santa Fe Railroad trestle have a steep northerly dip. The presence of a fault in Rose Canyon is evidenced by the difference in altitude of beds on opposite sides of the canyon. Apparently the southwest side moved northwestward, and beds on the west side of Mission Bay dropped down with respect to the beds on the east.

The Pliocene beds on the south slope of Soledad Mountain dip about 8° SE., an angle probably higher than their slope of initial deposition, and terraces on Soledad Mountain are higher than those that may be their correlatives in the mesa lands to the east. No evidence of Pliocene beds has been found on the north slope of Point Loma, and it appears that Mission Bay represents a syncline, the south limb of which has been dropped down along the north side of Point Loma by a fault that trends along Mission Valley. The beds

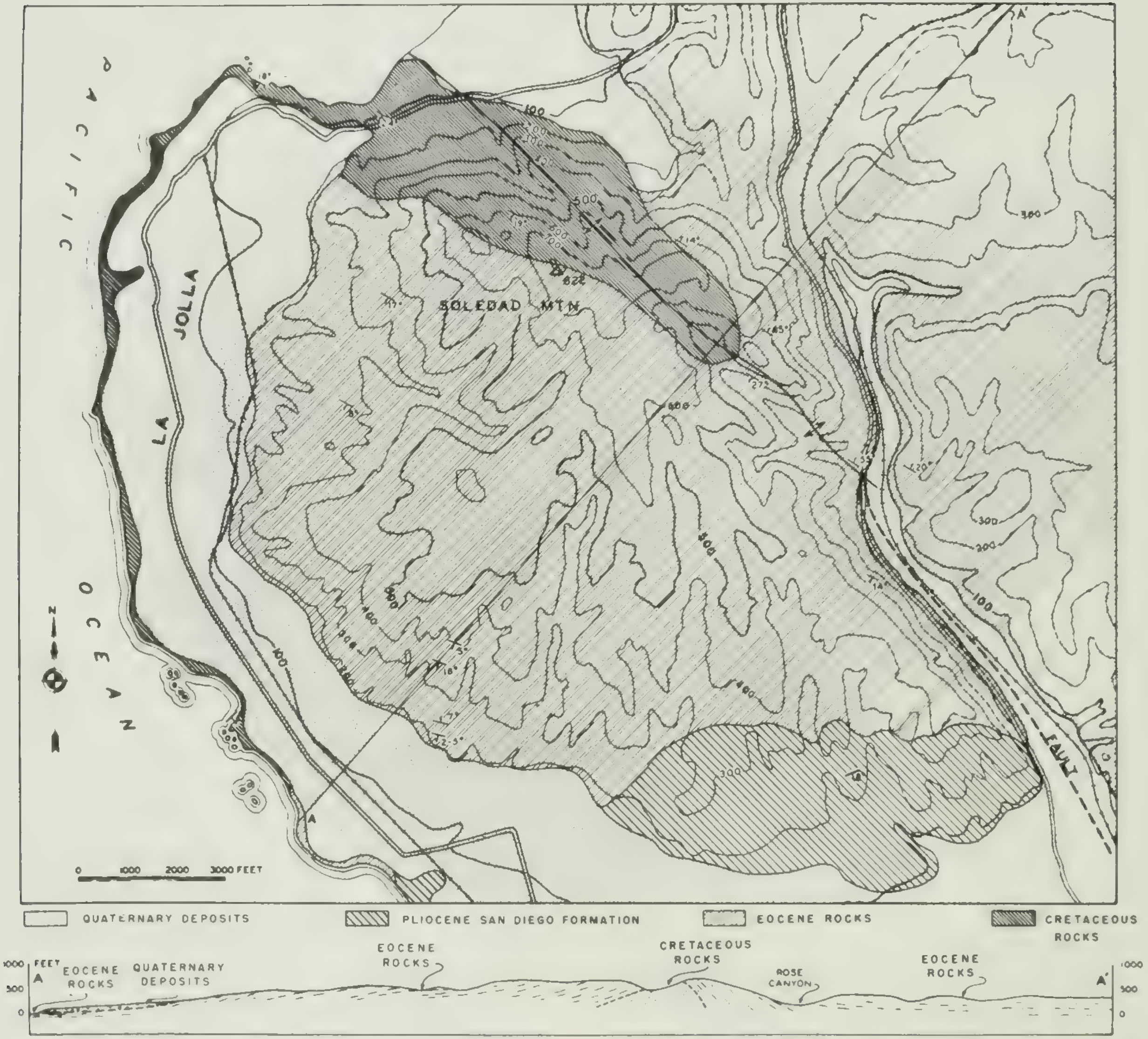

FIGURE 6. Geologic map and cross-section of the Soledad Mountain area. The thin veneer of terrace deposits is not shown on the map or section, but the Pleistocene and Recent alluvium on La Jolla terrace have been combined, and are shown together as Quaternary.

on Point Loma dip eastward 10° to 12°, and it appears likely that these beds have been tilted because of faulting along the western side of this block. Whether or not the Rose Canyon fault continues into San Diego Bay is not known.

The dip of most of the San Diego Pliocene beds is low, ranging from 6° to horizontal. Some of the conglomeratic beds in the Pliocene section along the international boundary near Tijuana dip about 9° W. These might represent foreset beds of an old delta that may have been tilted after its development.

Several small normal faults with a few feet of throw are exposed in bluffs and roadcuts in the mesa region south and east of San Diego. These and other small faults in the sea cliffs north of La Jolla are not shown on the accompanying map (fig. 1).

ECONOMIC GEOLOGY

More than fifty wells have been drilled in this area in an unsuccessful search for petroleum. The deepest holes reached points more than 5,000 feet beneath the surface, and penetrated the Black Mountain volcanics and metamorphics.

Some of the crystalline rocks in the area have been used for building purposes and for road metal. Clay for bricks and pottery has been obtained from the Eocene and Pliocene sediments. Bentonite has been mined at times from Pliocene beds on Otay Mesa. Common salt (NaCl), bromine, and magnesium salts have been obtained by solar evaporation of sea water in San Diego Bay.

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5. GEOLOGY OF THE LOS ANGELES BASIN *

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INTRODUCTION

The present-day Los Angeles topographic basin is a lowland close to the sea, and has been called a coastal plain (Mendenhall, 1905, p. 11). It has a northwest trend, and is 50 miles long and about 20 miles wide. Downtown Los Angeles is at the inner edge; Los Angeles harbor and the city of Long Beach are at the outer edge. The lowland is bounded on the northeast by the Puente Hills, on the east and southeast by the Santa Ana Mountains and San Joaquin Hills, and on the southwest by the Palos Verdes Hills and the Pacific Ocean (fig. 1).

The Los Angeles basin during Pliocene time was a marine embayment somewhat larger than the present lowland area. Its southwestern margin during most of this time probably was a shelf which, though submerged, was thousands of feet higher than the central part of the basin.

The basin during Miocene time was still larger, extending inland as far as Pasadena and Pomona and merging into the Ventura basin to the northwest. In this paper, the term ''Los Angeles basin'' refers to the large Miocene basin unless specifically qualified. During middle Miocene time the basin was bounded on the southwest by a land mass (Catalinia) that apparently was composed exclusively of glaucophane schist and related rocks.

Today the basin's central floor is buried beneath at least 20,000 feet of Miocene and later sedimentary rocks. A southwestern shelf has a crystalline schist floor (the Western bedrock complex) that is 1,000 feet above sea level in the Palos Verdes Hills, mostly 4,000 to 10,000 feet below sea level north of those hills, and as much as 14,000 feet subsea beneath Long Beach. A similar shelf on the northern and eastern sides of the basin is floored by pre-Upper Cretaceous crystalline rocks (the Eastern bedrock complex) at depths that probably range from about 15,000 feet subsea to approximately sea level. Farther east this complex rises abruptly to form the core of the Santa Ana Mountains and the high ranges to the east and north.

The Los Angeles basin is somewhat similar in its geologic history to the Ventura basin, 25 to 50 miles northwest. Each was a deep marine trough at the beginning of Pliocene time, and each was then filled successively with sediments containing fossils characteristic of shallower and shallower water, until the uppermost, largely continental, Pleistocene strata were deposited.

As shown in figure 1, the basin is divided structurally into fairly well marked blocks, mostly by major faults or fault zones. The Palos Verdes Hills block lies southwest of the Palos Verdes fault zone, the main West Side block lies between the Palos Verdes and the Newport-Inglewood fault zones, and the Central Deep block lies between the Newport-Inglewood zone and the curved margin of the eastern shelf. The eastern shelf is split by the Whittier fault into a northern or Puente Hills block and a southern or Anaheim-Santa Ana block. The Los Angeles basin as a whole is bounded on the north by the high-standing blocks of the Santa Monica and San Gabriel Mountains, and on the east by the Perris block and the Santa Ana Mountains block.

Within the individual fault blocks the most notable structural features are anticlines in the sedimentary rock cover. These range in length from 1 to 7 miles, and each probably is draped over a bulge in the crystalline floor. On the west side of the basin each anticline is an oil field, and the crystalline schist core of almost every anticline has been reached by wells.

The great event in the geologic history of southern California was the post-Triassic, pre-Upper Cretaceous diastrophism, plutonic intrusion, and metamorphism that produced the Eastern bedrock complex, and perhaps the Western bedrock complex, as well. Subsequent diastrophism has been more or less continuous. Notable folding, with or without faulting, occurred in the shelf areas during middle Miocene, latest Pliocene, and middle Pleistocene times.

The unmetamorphosed Upper Cretaceous and Cenozoic sedimentary rocks above the great unconformity are mostly marine and mostly clastic. Nonmarine varicolored clastic sedimentary rocks are known at the base of the Upper Cretaceous section, at the base of the Paleocene section, and in Oligocene and Miocene formations. The white-weathering Monterey shale of middle and late Miocene age, perhaps the most interesting formation in the area, is marine, mostly nonclastic, siliceous, and thinly laminated. It is interbedded with coarse clastic strata, notably the San Onofre breccia of western derivation.

STRATIGRAPHY

Eastern Bedrock Complex. The mountainous spine of southern California and Baja California consists chiefly of plutonic and metamorphic rocks, most of which are Mesozoic in age. Similar rocks underlie the eastern shelf of the Los Angeles basin, and they also form most of the bulk of the Transverse Ranges north and northeast of the basin.

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* Publication authorized by the Director, U. S. Geological Survey.

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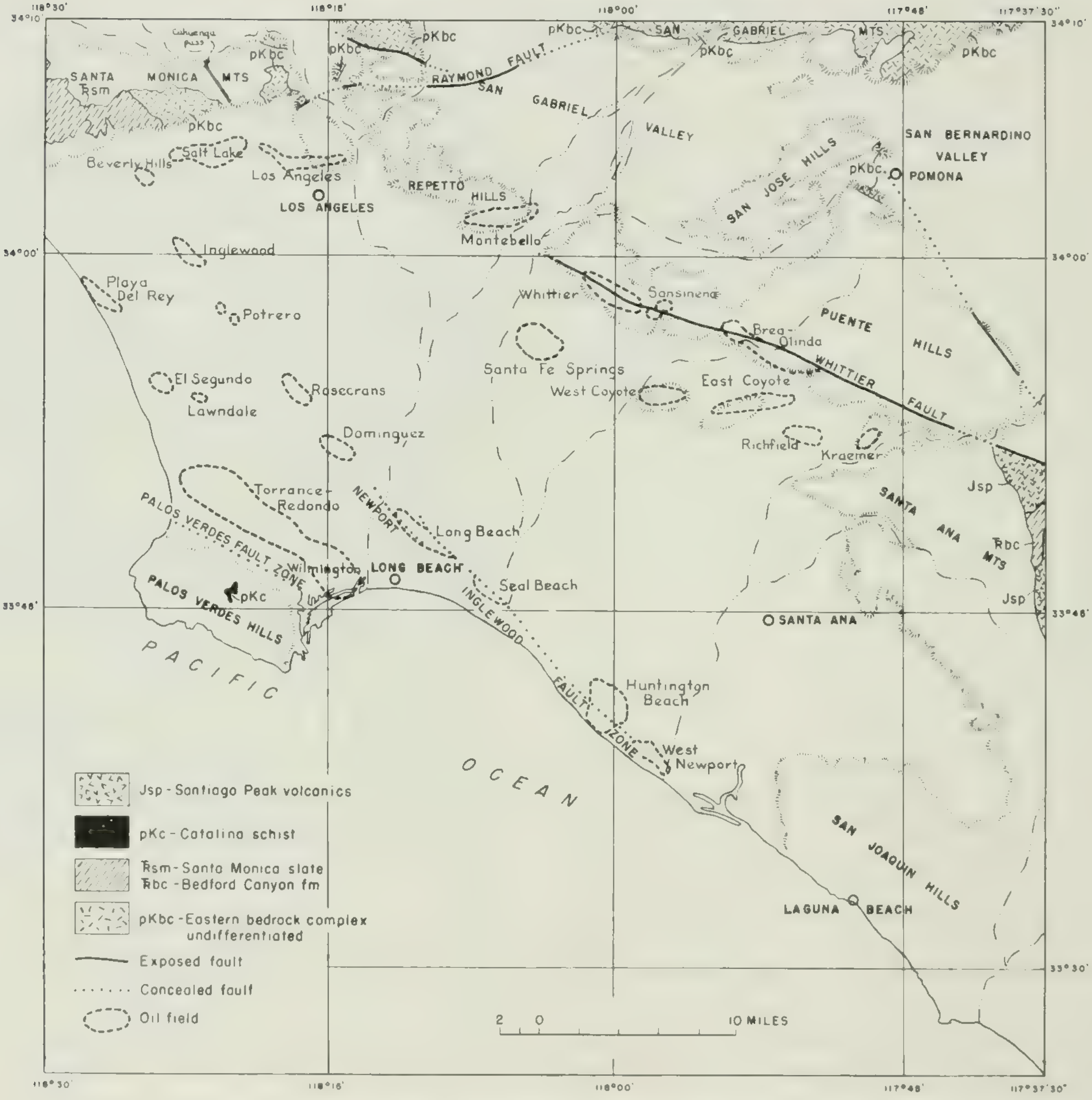

FIGURE 1. Index map of the Los Angeles basin, showing oil fields and distribution of exposed basement rocks.

The few fossils found in the metamorphic rocks of the Eastern bedrock complex are of Carboniferous age (Woodford and Harriss, 1928; Webb, 1939) or Triassic age (Larsen, 1948). Thousands of feet of limestone and quartzite are present, especially in the San Bernardino Mountains (eastern Transverse Ranges), and most of the section probably is of late Paleozoic age. The Bedford Canyon formation, of Triassic age (Larsen, 1948), includes many thousands of feet of slightly metamorphosed slate, argillite, and feldspathic quartzite, with a little limestone. It forms most of the core of the northern Santa Ana Mountains, just east of the Los Angeles basin, and similar rocks form most of the core of the Santa Monica Mountains northwest of the basin. In the Santa Ana Mountains the Bedford Canyon formation is overlain unconformably by the Santiago Peak volcanics, which crop out as a strip of steeply dipping, slightly metamorphosed flows, breccias, and tuffs, chiefly of andesitic or quartz latitic composition.

The great masses of plutonic rocks that intrude the metasediments and metavolcanics are mostly gabbro, quartz diorite, and granodiorite. The quartz-bearing rocks contain abundant biotite and hornblende. Plutonic rocks form the most common type of bedrock encountered in wells that penetrate the sedimentary cover of the basin's eastern shelf.

The San Gabriel Mountains, northeast of the basin, consist chiefly of gneissic and plutonic rocks, and the latter are somewhat similar to those just described. These rocks are shown on the geologic map (pl. 1) as ''basement'' rocks, following the usage of Shelton (1946). Also exposed in these mountains, especially along their northeastern margin (beyond the limits of the map), is the chloritic and albitic Pelona schist, a fine-grained rock with a distinctive crinkly structure. This rock has been referred to the pre-Cambrian by Simpson (1935, pp. 377-378). Bedrock that resembles the Pelona schist has been found in wells at Brea Canyon, in the Puente Hills just northeast of the Whittier fault.

The structural features in the bedrock east of the Los Angeles basin commonly strike north-northwest, parallel to the elongation of the ranges. In the Transverse Ranges the major elements of bedrock structure commonly strike east, parallel to the elongation of those ranges. Stratification and slaty cleavage in the Bedford Canyon formation commonly are nearly perpendicular to the bedding in the overlying younger strata.

Western Bedrock Complex (Catalina Schist). The fine-grained schists that crop out in the Palos Verdes Hills and underlie the Los Angeles basin southwest of the Newport-Inglewood fault zone are characterized by abundant chlorite, quartz, moscovite, and albite, as well as by the presence of glaucophane and lawsonite. Mineralogically similar rocks make up a large part of Santa Catalina Island, 20 miles offshore, although there the rocks are in part massive, rather than schistose, and contain numerous relics of sedimentary structures, such as shale flakes (Bailey, 1941; Woodford, 1924, p. 57).

The Catalina schist in the Los Angeles basin is composed chiefly of fine-grained, gray-green, chlorite-bearing schists, including muscovite-chlorite schist, muscovite-chlorite-quartz schist, and albite-chlorite-quartz schist. Most of these are metasediments and metatuffs. Bodies of metamorphosed intrusive rocks, including serpentine rock and ''saussurite gabbro,'' are rarer. Glaucophane, lawsonite, actinolite, and members of the epidote group are widespread but rarely abundant minerals in this terrane.

Planes of schistosity in the Catalina schist are well marked, very closely spaced, and crumpled. Many laminae are present in each millimeter of rock. The crumpled foliation surfaces generally have average dips of less than 45°, and commonly are nearly parallel to the stratification planes in the overlying Miocene sedimentary rocks.

The Catalina schist may be Mesozoic (Franciscan, cf. Bailey, 1941), or it may be pre-Cambrian in age. In composition and texture, it resembles the schist bodies in the typical Franciscan sedimentary rocks of central California, but it differs from them by its vastly greater bulk. In texture it somewhat resembles the pre-Cambrian(?) Pelona schist.

Upper Cretaceous Rocks. A thick and varied section of Upper Cretaceous sedimentary rocks is exposed discontinuously from the Simi Hills, north of the Santa Monica Mountains, southeastward along the coast to Baja California.

Within the Los Angeles basin these Upper Cretaceous clastic rocks are exposed in the Santa Monica Mountains on the northwestern edge of the basin, and in the Santa Ana Mountains on the basin's eastern margin. They probably are present beneath a thick Tertiary cover in the deep central part of the basin, as well.

In the Santa Monica Mountains the undifferentiated Upper Cretaceous rocks, commonly called Chico formation, rest unconformably on the Santa Monica slate of Triassic(?) age (Hoots, 1931, p. 90), and on granite and granodiorite of Jurassic(?) age (Durrell, Map sheet No. 8). The exposed section has a maximum thickness of about 7,000 feet, and consists of interbedded coarse conglomerate, feldspathic sandstone, and minor amounts of dark gray to black shale. From near the top of this section, Popenoe (1942, p. 184) reports an Upper Cretaceous fauna of ammonites, pelecypods, and gastropods.

In the Santa Ana Mountains the Upper Cretaceous rocks are about 5,500 feet in maximum thickness. They consist of interbedded coarse conglomerate, feldspathic sandstone, and dark gray to black shale and siltstone that rest unconformably on the Bedford Canyon for-

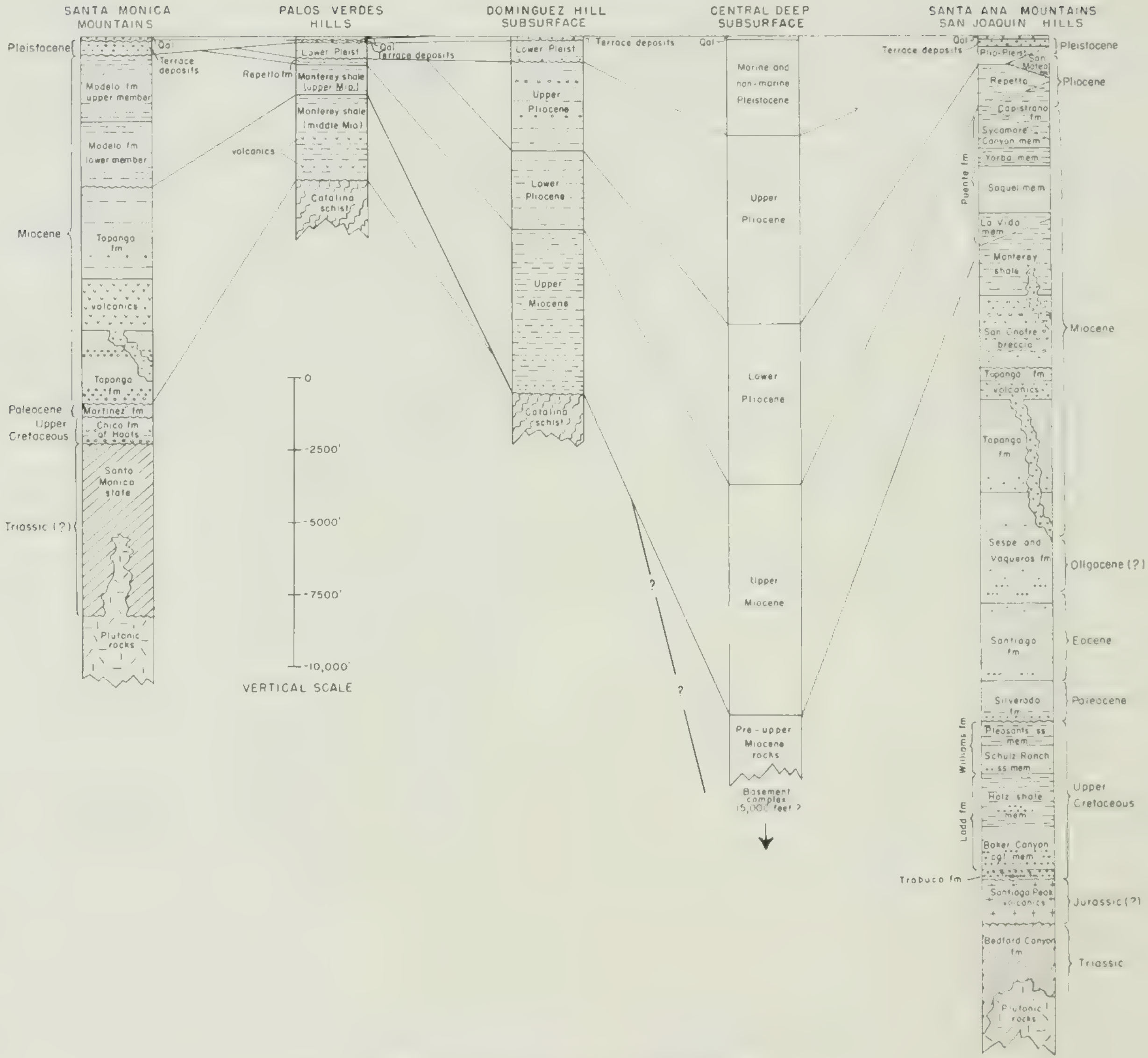

FIGURE 2. Columnar section, Los Angeles basin.

mation of Triassic age and the Santiago Peak volcanics of Jurassic(?) age (Larsen, 1948, p. 22).

Packard (1916, p. 140) applied the name Trabuco formation to the red and white nonmarine conglomerates at the base of the Upper Cretaceous section. Popenoe (1942, pp. 170-175) subdivided the marine part of the section into two formations with two members in each. These are the Ladd formation, comprising the Baker Canyon conglomerate member and the Holz siltstone, sandstone, and conglomerate member, and the Williams formation, comprising the Schulz Ranch sandstone member and the Pleasants fine-grained sandstone member.

Both the Ladd and Williams formations contain many pelecypods and gastropods of Upper Cretaceous age. Ammonites found in the Pleasants sandstone member of the Williams formation may be correlative with those obtained from the Santa Monica Mountains (Popenoe, 1942, p. 185).

Paleocene Rocks. Rocks of Paleocene age crop out in both the Santa Monica Mountains and the Santa Ana Mountains, and probably underlie a considerable area in the eastern part of the Los Angeles basin.

Hoots (1931, p. 91) called the Paleocene rocks in the western part of the area covered by his map the Martinez formation. Durrell and others at the University of California at Los Angeles have traced a thin strip of Martinez sandstone and conglomerate eastward along the north limb of the eastern Santa Monica Mountains anticline.

In the Santa Ana Mountains a maximum of about 1,400 feet of Paleocene sedimentary rocks is exposed. These rocks rest unconformably on the Upper Cretaceous strata, and, near the town of Corona, directly on the Eastern bedrock complex. English (1926, p. 19) called the Paleocene rocks the Martinez formation, and Woodring and Popenoe (1945) later renamed them the Silverado formation.

The basal part of the Silverado formation is nonmarine conglomerate with subangular clasts derived from the basement core of the Santa Ana Mountains. Above this is a series of alternating white to buff feldspathic sandstones, with altered biotite flakes that locally are so abundant that the rock resembles biotite schist. An easily recognized bed of brown to maroon pisolitic clay, 1 to 6 feet thick, is commonly present in this part of the section, and is locally accompanied by beds of carbonaceous shale and very low grade lignite. The upper part of the Silverado formation is a yellowish green to buff sandstone that contains a molluscan fauna of Paleocene age.

Eocene Rocks. Eocene rocks are known only in the Santa Ana Mountains. They were correlated with the Tejon formation of central California by English (1926, p. 21), and were renamed the Santiago formation by Woodring and Popenoe (1945).

The Santiago formation has a maximum thickness of about 2,700 feet, and rests with apparent conformity on the Silverado formation. Commonly the base is marked by a thin conglomerate. Above this conglomerate is a series of fine- to medium-grained, buff to greenish gray sandstone beds that contain a middle Eocene molluscan fauna. These beds grade upward into white, coarse, feldspathic sandstone containing local lenses of conglomerate, thin lenses of silt that commonly is greenish in color, and scattered pieces of silicified wood.

Oligocene(?) and Lower Miocene Rocks. The nonmarine Sespe formation and the marine Vaqueros formation of the San Joaquin Hills and the Santa Ana Mountains commonly are mapped as a single undifferentiated unit (English, 1926; this report, pl. 1). Their combined maximum thickness is about 3,000 feet along the southwest side of the Santa Ana Mountains, and at least 3,200 feet in the San Joaquin Hills (Dolton, 1952). They rest with apparent conformity on the Santiago formation in the Santa Ana Mountains; the base has not been mapped in the San Joaquin Hills.

The lower or Sespe part of this series is composed of nonmarine interbedded earthy sandstone, conglomerate, and siltstone. These rocks are varicolored, ranging from white, buff, and gray through various shades of green to deep red and maroon. In general they are poorly cemented and soft, and they erode easily into badlands. In the Santa Ana Mountains it has not been possible to draw a line between the Sespe formation and the overlying marine Vaqueros formation. Locally mollusks of Vaqueros age are present in red and maroon beds of the Sespe type. Although the nonmarine strata of the Sespe formation in this area have yielded no fossils, they probably range in age from late Eocene to earliest Miocene.

The Vaqueros formation of early Miocene age (Loel and Corey, 1932) overlies the Sespe formation and also intertongues with it. The Vaqueros consists mainly of gray to buff sandstone, conglomerate, and local greenish gray sandy siltstone. Many of the sandstone beds are carbonate-cemented, and stand out in bold relief above the weak Sespe strata. *Turritella* and oyster reefs can be traced for distances of a mile or more. Lower Miocene mollusks of shallow-water types are abundant throughout the Vaqueros; these have been described by Loel and Corey (1932, pp. 51-60).

Middle Miocene Rocks. Middle Miocene sedimentary rocks are widely distributed and highly varied. They include sandstone, conglomerate, breccia, diatomite, and organic shale. The coarse clastic rocks of the Topanga formation contain shallow-water marine fossils, and are present at the northwest, northeast, and southeast margins

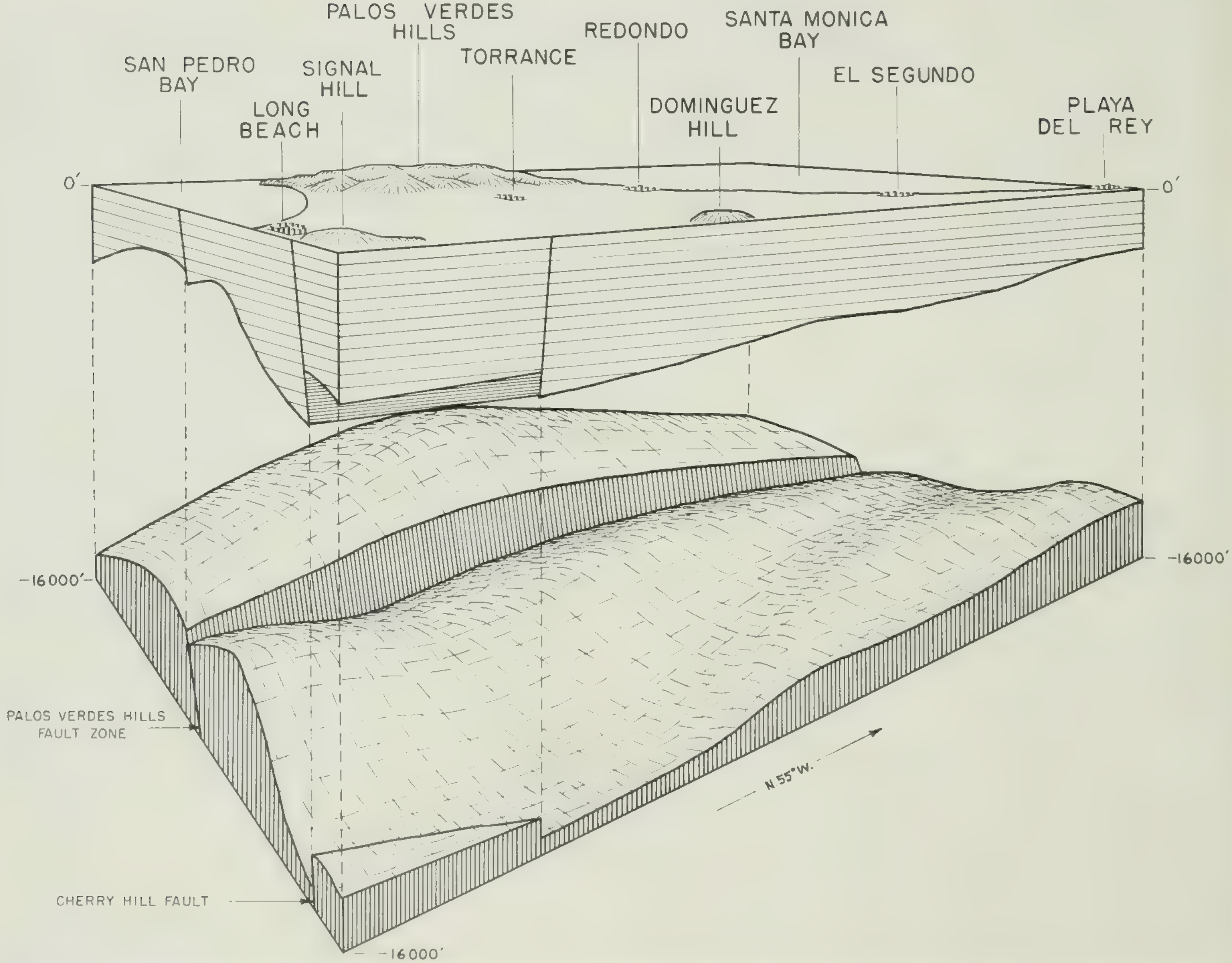

FIGURE 3. Block diagram of west side of Los Angeles basin. The cover of sedimentary rocks is lifted to show the form of the surface on the Catalina schist.

of the basin. The northeastern exposures are much less fossiliferous than those elsewhere, but the Buzzard Peak conglomerate member of the Topanga formation in the northeastern San Jose Hills contains specimens of *Aequipecten andersoni*, and in the subsurface the conglomerate grades southwestward into shale containing middle Miocene Foraminifera. The Monterey shale, which is organic to cherty and weathers white, crops out in the San Joaquin Hills and Palos Verdes Hills bordering the ocean, and probably is present throughout the entire deep central part of the basin. The foraminiferal assemblage suggests shallow bathyal deposition, perhaps between 600 and 2,000 feet, on the basis of the depth ranges of both the genera and the Recent species that are included.

The San Onofre breccia of the San Joaquin Hills, included in the Temblor formation by Woodford (1925, pp. 169, 182) and more recently included in the Topanga formation by several geologists, is here set off as an independent unit, chiefly because it is locally separated from the underlying main part of the Topanga formation by a notable unconformity. The San Onofre breccia is composed almost exclusively of fragments of glaucophane schist and related rocks of the Western bedrock complex (Catalina schist), with numerous blocks 3 to 10 feet in diameter. It is interbedded with Monterey shale that contains middle or late Miocene fish scales (oral communication from Richard Pierce; see fig. 5), and is overlain by Monterey shale with middle Miocene Foraminifera. The schist breccia lens of figure 5 is 200 feet thick. The hundreds of 3- to 7-foot slabs of schist exposed in the beach section are all blue glaucophane schist or green epidote-bearing schist. The lens includes at least two bouldery units, separated in part by well-sorted fine-grained sandstone and siltstone wholly derived from schist. Coarse breccia grades into finer clastic rocks seaward, or westward, toward the presumed source.

The sediments of the Topanga formation have a maximum thickness of 7,500 feet in the Santa Monica Mountains at the northwest corner of the basin (Hoots, 1931, p. 88), 2,000 feet in and near the San Jose Hills at the north edge of the basin, and as much as 3,500 feet in the San Joaquin Hills at the southeast edge of the basin. The middle Miocene portion of the Monterey shale is 400 to 3,000 feet thick (Woodring, et al., 1946, p. 13). The maximum thickness of the main body of the San Onofre breccia, in the sea cliffs southeast of Laguna Beach, is about 2,500 feet.

Most of the middle Miocene sedimentary rocks are marine, and much of the Monterey shale may even be a deep-sea deposit. The Buzzard Peak conglomerate member of the Topanga formation, on the northeast margin of the basin, and the San Onofre breccia at its southeast edge may be mostly continental.

Middle Miocene volcanic rocks, mostly calcic andesite flows, tuffs, and breccias, are found in almost all parts of the basin. They range from local thin beds of tuff to the 3,000 feet of lava, breccia, and other rocks that underlie the eastern part of the present San Gabriel basin (northeastern part of the Miocene Los Angeles basin). The Miocene volcanic rocks of the Los Angeles basin area are described elsewhere in this volume by Shelton (Contribution 4, Chapter VII) and Durrell (Map sheet No. 8). Large dikes of diabase and andesite in the San Joaquin Hills radiate from the vicinity of Laguna Beach. These may be in part contemporaneous with the middle Miocene volcanic rocks, although one member of this dike complex cuts late Miocene Monterey shale.

Upper Miocene Rocks. Sedimentary rocks of late Miocene age reach a maximum thickness of about 11,000 feet in the Los Angeles basin. They crop out in all of the hills surrounding the basin, and are present beneath most of the alluvium-mantled central plain.

In the Santa Monica Mountains west of Cahuenga Pass, the name Modelo formation is applied to the rocks of late Miocene age (Hoots, 1931). Eastward through the Puente Hills and the Santa Ana Mountains, rocks of similar lithology are called the Puente formation (Eldridge and Arnold, 1907, pp. 103, 143, 145).

Along the coast from the Palos Verdes Hills southeastward to Dana Point, siltstone, diatomaceous shale, and radiolarian mudstone of late Miocene age are included in the Monterey shale, which is in part of middle Miocene age. At the southeastern end of the basin the Monterey shale is overlain unconformably by the basal breccia and sandstone of the Capistrano formation (Woodford, 1925, p. 216), whose foraminiferal faunas indicate late Miocene to early Pliocene age.

On the geologic map (plate 1) the Modelo formation has been divided into two members. The lower member has a maximum thickness of about 2,750 feet, and consists of white porcellaneous shale, brown shale, and coarse-grained sandstone. The upper member, 2,300 feet thick, is diatomaceous shale with interbedded sandstone (Hoots, 1931, p. 102). The Modelo formation contains a late Miocene foraminiferal fauna.

The Puente formation reaches a maximum thickness of about 11,000 feet in the Puente Hills, along the northern margin of the Los Angeles basin. It has been divided into four members by Schoellhamer, et al. (1953). These are, in ascending order, the La Vida member, consisting of gray to black laminated siltstone with interbedded feldspathic sandstone; the Soquel member, consisting of massive to moderately well-bedded, coarse to gritty feldspathic sandstone; the Yorba member, consisting of thin-bedded gray siltstone, diatomaceous siltstone, and local strata of sandstone and conglom-

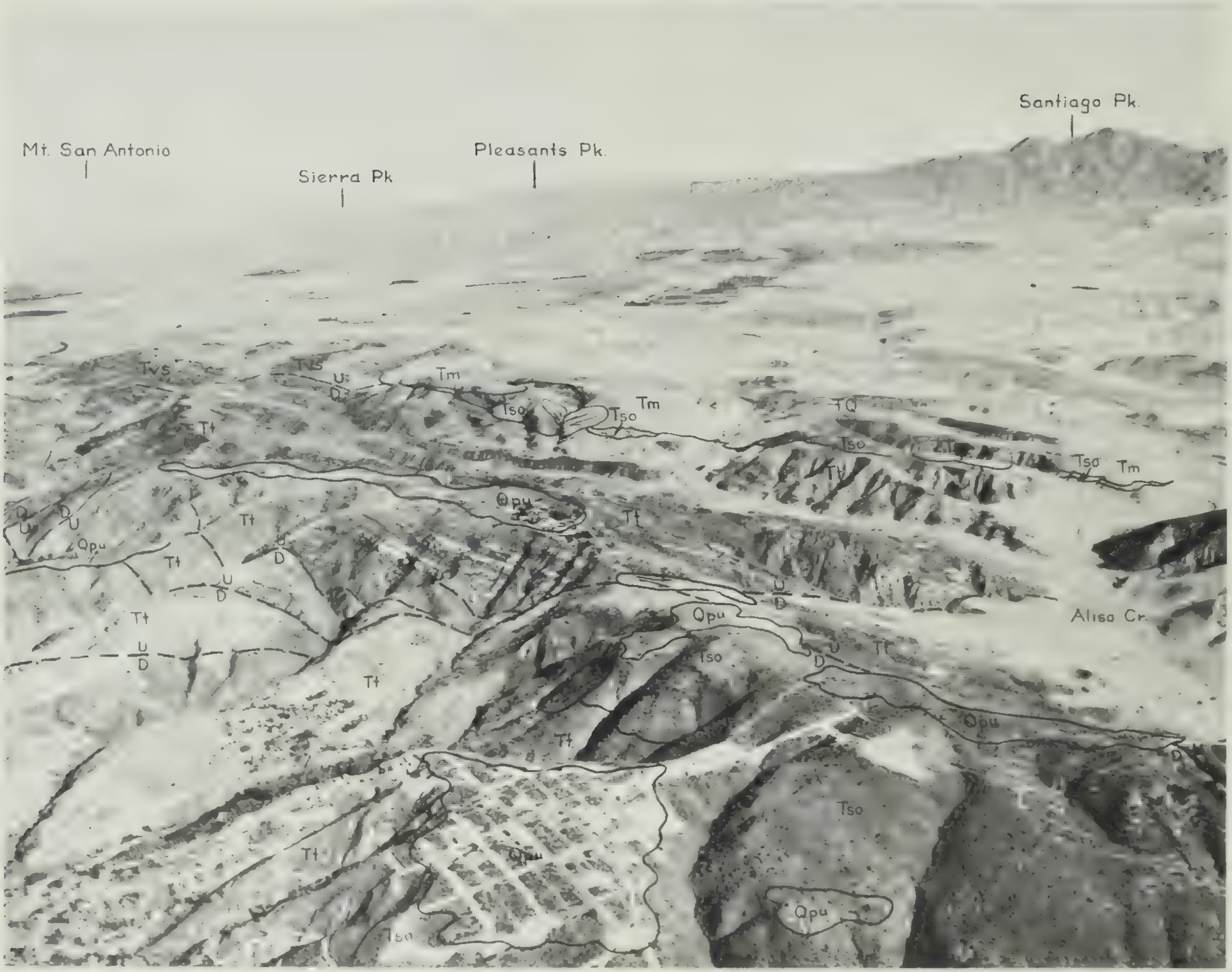

FIGURE 4. High oblique aerial view of eastern San Joaquin Hills and Santa Ana Mountains from the southwest. Tvs, Vaqueros-Sespe; Tt, Topanga; Tso, San Onofre; Tm, Monterey; TQ, Pliocene or Pleistocene, undifferentiated; Qpu, Pleistocene terraces. Solid lines, normal contacts. Dashed lines, faults; U, upthrown; D, downthrown. *Photo by J. S. Shelton and R. C. Frampton.*

erate; and the Sycamore Canyon member, consisting of interbedded conglomerate, micaceous siltstone, and sandstone.

On the west side and in the deep central part of the Los Angeles basin, it is impossible to make these lithologic distinctions within the upper Miocene strata, although the rocks can be divided on the basis of foraminiferal faunas (Wissler, 1943, p. 210).

Pliocene Rocks. Marine sedimentary rocks of Pliocene age attain a known thickness of at least 10,000 feet in the deep central part of the Los Angeles basin, and they may be considerably thicker. In this central deep these rocks consist of interbedded greenish gray micaceous siltstone and fine- to coarse-grained, light gray feldspathic sandstone. Pebble conglomerates and fine rubble breccias are present locally, and become more numerous toward the top of the Pliocene section. The foraminiferal faunas from the lower Pliocene rocks in the central part of the basin indicate that these sediments were deposited in water more than 4,000 feet deep (Natland, 1952, p. 50). During late Pliocene time the sea shallowed gradually to about 900 feet (Natland, 1952, p. 50).

Conditions of continuous deposition in deep water make it impossible to subdivide the Pliocene rocks of most of the basin into formations, although foraminiferal zones can be distinguished (Wissler, 1943, p. 210). Numerous exposures of Pliocene rocks are present in the hills that surround the present-day Los Angeles basin. These strata were deposited close to the margins of the Pliocene sea, and conditions of deposition were varied enough so that lithologic differences in the Pliocene rocks can be recognized.

The lower Pliocene rocks, commonly called Repetto formation, were described from exposures along Atlantic Boulevard in the eastern part of the Repetto Hills, east of Los Angeles (Reed, 1933, p. 229). The formation is mostly siltstone, with a few thin layers of sandstone and conglomerate that locally contain fragmental remains of shallow-water mollusks. In the nearby Montebello oil field these rocks are 4,500 feet thick. The name Repetto is now in general use for rocks of early Pliocene age throughout the Los Angeles basin, and determinations are made on the basis of foraminiferal assemblages.

On the geologic map of the Los Angeles basin (plate 1), Reed's Repetto formation is shown in the Palos Verdes Hills, Los Angeles City, Montebello Hills, northwestern Puente Hills, eastern Puente Hills, and along the northwest tip of the Santa Ana Mountains near the town of Olive.

In the northwestern Puente Hills, north of the town of Whittier, a sequence of alternating siltstones and conglomerates about 1,700 feet thick rests conformably on the rocks called Repetto. The upper member of this sequence contains a large molluscan fauna of late Pliocene age (Stark, 1949), with *Anadara trilineata* and *Patinopecten healeyi*. An even larger, perhaps equivalent molluscan fauna is present in the south-dipping strata of downtown Los Angeles, from 6th and Figueroa Streets to 4th and Hill Streets (Soper and Grant, 1932). Foraminifera are present in the finer-grained sediments, and on the basis of the microfauna the entire sequence was assigned to the Pico formation by Wissler (1943). The type locality of the Pico is in the Ventura basin (see Bailey and Jahns, Contribution No. 6, this chapter). This sequence and some probable correlatives south of the Whittier fault as far east as Brea are marked Tpu on the geologic map (plate 1).

A slightly consolidated, largely marine sand and conglomerate formation of late Pliocene(?) and/or Pleistocene age, which occurs near the top of the section on the east side of the Los Angeles basin, has been called the La Habra conglomerate by Eckis (1934). It is overlain unconformably by Pleistocene continental red alluvium, which perhaps should be included with the San Dimas formation of Eckis (1934).

Elsewhere around the margin of the Los Angeles basin, it has been necessary to group rocks ranging in age from early Pliocene to early Pleistocene into a single map unit because of their similar lithology or because of the lack of detailed geologic maps. Included in these rocks is the San Mateo formation (Woodford, 1925, pp. 217-219), which is exposed southeast of the San Joaquin Hills.

Pleistocene Rocks. The Pleistocene record is a complicated one, involving marine and continental formations, warping, and middle Pleistocene angular unconformities at the margins of the basin.

In general the Pleistocene sediments are marine along the ocean and become continental 5 to 10 miles inland. At Stanton, 10 miles east of Signal Hill and near the center of the modern basin, continental sand and silt prevail from the surface to a depth of 3,200 feet, although below 1,050 feet some layers contain lagoonal and neritic Foraminifera. These beds are underlain by silt and sand that contain uppermost Pliocene Foraminifera of moderately shallow-water facies (determinations by M. L. Natland). Toward the ocean the continental Pleistocene sediments thin rapidly and are replaced by marine sand and silt, first with shallow-water Foraminifera and then with abundant shallow-water mollusks. Nearly all of these can be assigned to living species.

In determining the thickness of the Pleistocene section and the areas of Pleistocene outcrop we have followed Poland and others (1945, 1946). Other workers make the marine Pleistocene section many hundreds of feet thicker and the areas of Pleistocene outcrop slightly more extensive.

The San Pedro (Los Angeles Harbor) Pleistocene section (fig. 7) is unusually complex. The Lomita marl, at the base, lies with marked unconformity on the organic shale, porcellanite, and chert of the Monterey shale. The Lomita is composed chiefly of the remains of Mollusca, Bryozoa, Foraminifera, and other invertebrates, with a few dark-brown phosphatic nodules and fairly numerous grains of chert and porcellanite of the Monterey. The overlying Timms Point silt and San Pedro sand, also highly fossiliferous, consist chiefly of grains of quartz and feldspar and flakes of biotite, brought from a northern or northeastern granitic source across the width of the Los Angeles basin. The change from Lomita marl to Timms Point silt, which is sharp in some places and gradational in others, marks a notable change in Pleistocene paleogeography. The Lomita probably is an offshore reef deposit that marks the position of an ancient submarine ridge that antedated the present Palos Verdes Hills. The reefs were separated from the mainland by moderately deep water that may have covered a large part of the present Los Angeles basin. The northeastern derivation of the Timms Point silt indicates that the basin of Lomita time had been gradually filled, allowing granitic debris to be carried across its full width.

A set of added complications should be noted. Marine sand and silt of San Pedro and Timms Point types, and which contain similar mollusks, are involved in folding and are exposed on the crests of the Signal Hill and West Coyote anticlines, one on each side of the continental section in the center of the basin at Stanton. One explanation of this anomaly is that the section at Stanton represents an alluvial lobe extending from the east into the shallow bay that covered much of the Los Angeles basin during San Pedro and Timms Point time.

One of the best-known features of the Pleistocene rocks in southern California is the middle Pleistocene unconformity that was emphasized by Reed (1933), and that has been made the basis of the Pasadenan orogeny by Stille (1936, p. 867). This is shown in figure 7 as the line between the horizontal Palos Verdes sand of the lowest marine terrace in the Palos Verdes Hills and the series of deformed older strata ranging from upper Miocene rocks to San Pedro sand.

The Palos Verdes sand is locally crowded with marine shells. For example, Willett (1937, p. 381) collected and examined more than a million shells from a single one-foot layer near Playa del Rey. The greater part of the Palos Verdes and other terrace deposits is now covered chiefly with nonmarine accumulations, mostly the products of rill wash and weathering. The low marine terraces are overlain by great sand dunes in a broad belt extending north from the Palos Verdes Hills.

The higher and earlier terraces of the Palos Verdes Hills and other coastal highlands are mostly horizontal or nearly so. Thirteen major terraces (fig. 8) are present in the Palos Verdes Hills, the highest at an elevation of 1,300 feet. Similar terraces are present in the San Joaquin Hills, and the highest is 1,100 feet above sea level. The lower terraces on the San Joaquin Hills, as well as the summits of the Costa Mesa, Huntington Beach, and other mesas to the northwest, decrease in elevation inland until they disappear beneath the alluvial plain (plate 1). Apparently the modern basin has been deformed continuously up to very recent times, with its center sinking and at least part of its margin rising.

The continental sediments are much less fossiliferous than the marine beds, but they are far from barren. Bones of mammoth, horse, sloth, and camel have been found in many places, almost invariably in weathered, reddish alluvium (Qpu in plate 1). The most notable exception is the Rancho La Brea locality, at Wilshire and La Brea Boulevards in Los Angeles, where hundreds of thousands of late Pleistocene bones have been removed from asphalt pipes. The principal Rancho La Brea collection is in the Los Angeles County Museum, in Exposition Park. Many of the large land vertebrates that are present in the asphalt are also known from the marine sediments of the Palos Verdes section at San Pedro. This and all other known evidence indicate the approximate contemporaneity of the upper part of the reddish continental alluvium and the lowest of the nearly horizontal coastal marine terraces.

STRUCTURE

Major Faults. The primary elements in the structure of the Los Angeles basin are basement blocks separated by steep fault zones (cf. Driver, 1948, p. 112). The two fault zones of principal interest are the Whittier and the Newport-Inglewood, because they probably mark the boundaries between basement rocks of different composition and different facies. There also is considerable doubt, for each of these zones, about the amount and direction of the net total displacements.

The Newport-Inglewood fault zone is bounded on the southwest by the Western bedrock complex, one of the world's largest masses of rocks belonging to the glaucophane schist facies. There is nothing like these rocks to the east, short of the island of Anglesey, North Wales. The Catalina schists and associated rocks are highly variable, and consistently so. They do not show the slightest suggestion of gradation into any of the rocks prevalent in the basin portion of the Eastern bedrock complex.

Northeast of the Newport-Inglewood zone, in the broad belt that includes both the Santa Ana and the Santa Monica Mountains, the most distinctive bedrock types are slaty siltstone, graywacke, and

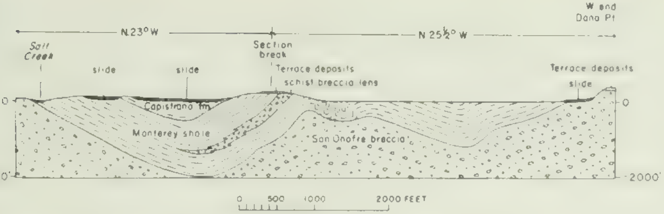

FIGURE 5. Structure section along beach from Salt Creek to Dana Point.

fine-grained sandstone of more or less definite Triassic age. In general, these rocks have undergone very mild metamorphism and clastic textures are well preserved. We may guess that similar rocks make up part of the bedrock that lies buried beneath the basin's central deep.

Possibly the Western bedrock complex is a pre-Cambrian or Paleozoic mass that has been faulted up against Triassic metasediments. One might even imagine that Triassic sediments had been deposited on the Western bedrock complex and then were removed by erosion, but there is no supporting evidence for this. Southwest of the Newport-Inglewood zone no body of quartz plutonite has been found, no remnant of downfaulted or downfolded Triassic rocks, and no sign of any member of the Eastern bedrock complex.

Another possibility is that the Catalina schist is of Mesozoic age, like the lithologically similar schists of the Franciscan formation farther north. Some of the Catalina metasediments might even have been deposited contemporaneously with the Triassic slates now found across the great fault zone. If contemporaneous, they cannot have been such close neighbors as they now are. The two series were unlike when they were formed, and they have undergone dissimilar types of metamorphism. They must have been brought into juxtaposition by great fault displacements, involving either overthrusting or strike-slip movements. The present relations do not encourage either hypothesis. The apparently steeply dipping contact and the absence of known klippen are unfavorable to a hypothesis of overthrusting, and the westward curve that would be needed in the Newport-Inglewood zone to extend it around the west end of the Santa Monica Mountains makes improbable a simple strike-slip displacement of the San Andreas type.

The Whittier fault zone is better known than the Newport-Inglewood zone, but it still is not well understood. It crops out at the surface in a slightly sinuous, locally branching line that trends about N. 70° W. for 25 miles, from Whittier almost to Corona, and frays out at each end into two or three branches or continuations (notably the Elsinore fault from Corona southeast), all of which trend more nearly north than the Whittier fault itself. The dip is 65° to 75° NE. in the western and central Puente Hills, but becomes nearly vertical or even is inclined toward the southwest near and south of the Santa Ana River. If the displacement is mostly dip slip, the fault must be of the reverse type in the western Puente Hills, with the northeast side moving up. In the eastern Puente Hills, however, the apparent displacement is downward on the north. The apparent reversal of the displacement is sudden, at a cross fault at Horseshoe Bend of the Santa Ana River (near east edge of plate 1).

If the displacement is in part strike slip, the cross fault at Horseshoe Bend may be correlative with the one at Scully Hill, but now separated from it by a right-lateral offset of about 15,000 feet. In fact, the only known solution for the total movement on the fault seems to include this strike slip, together with elevation of the Puente Hills block, especially at the northwest end of the fault zone, and an earlier elevation of the Santa Ana Mountains block at the southeast end. The maximum relative rise of the western Puente Hills on this fault may be about 10,000 feet.

The Whittier fault is nearly parallel to the major faults in the San Gabriel Mountains and other Transverse Ranges north of the Los Angeles basin. Even the San Andreas fault in this part of its course has almost the same trend. Perhaps the Whittier fault is one of the less typical members of the San Andreas system; possibly it is a secondary fracture related to the big bends in the San Andreas itself.

The movement on the Whittier fault is, so far as is known, wholly post-Topanga (middle Miocene) and mostly post-Pliocene in age. Upper Pliocene strata are offset almost as much as the earlier rocks, although even the lower Pliocene section south of the fault contains breccias (of probable deep submarine origin) that include fragments of shale from the Puente formation. South of the fault the only formation composed chiefly of locally derived fragments from the Puente formation is late Pleistocene in age (included in Qpa on plate 1) and is practically undeformed.

The Newport-Inglewood fault zone, on the other hand, is an old one on which activity may have been decreasing, even though movement here was responsible for the Long Beach earthquake of 1933. Wells in the Long Beach oil field, on and near Signal Hill, have penetrated a horst of schist at about 10,000 feet subsea. This basement horst has risen about 4,000 feet on the Cherry Hill fault (fig. 3), but identifiable horizons in the overlying sedimentary rocks are displaced less and less at higher and higher levels. The displacement on the basement fault is taken up in part in the overlying

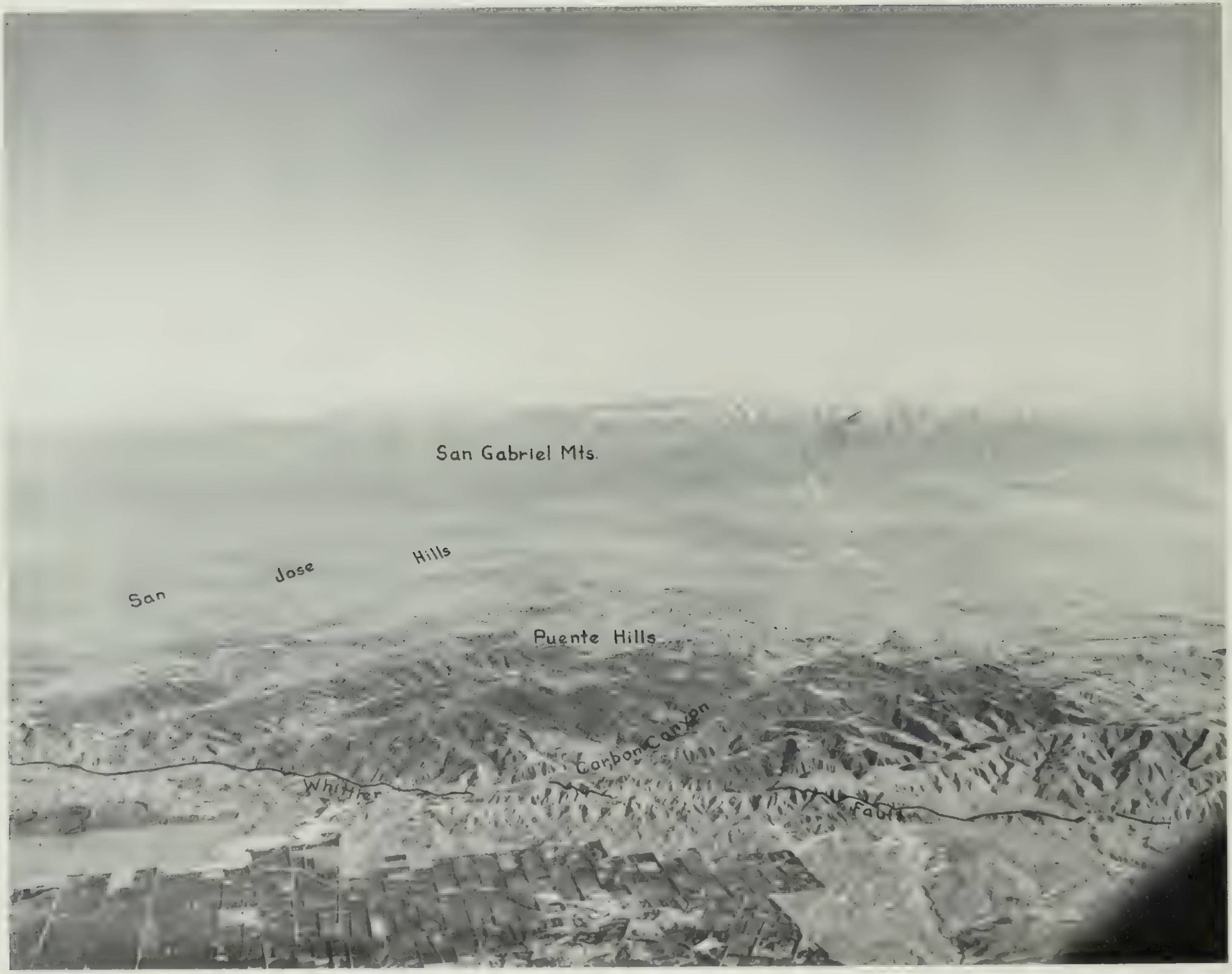

FIGURE 6. High oblique aerial view of Puente Hills from the south. *Photo by J. S. Shelton and R. C. Frampton.*

Signal Hill anticline, but some fault movement must also have preceded the deposition of the younger strata. At the surface, here and elsewhere along the Newport-Inglewood zone, folding is more prominent than faulting. The late Tertiary and Quaternary faulting cannot be ignored, however, and some right-lateral strike slip is said to have been demonstrated by subsurface studies.

Folds. The folding of sedimentary rocks in and near the Los Angeles basin is primarily incidental to the deformation of the basement rocks. Some folds, such as the Signal Hill and Dominguez anticlines, overlie known or probable basement horsts along the Newport-Inglewood zone. Other folds on the west side of the basin, such as the anticlines at Wilmington, Torrance, El Segundo, and Playa del Rey, are draped over basement highs that may have been initial buried hills, at least in some instances, but seem also to have risen through plastic deformation. On the east side of the basin, bedrock cores have not yet been encountered in the anticlines, although the existence of such cores can hardly be doubted, especially in view of unpublished gravity data. Several east-side folds are complicated by unconformities (structure sections GH and IJK).

An attempt to explain the anticlines of the Los Angeles basin may well take into account (a) the right-lateral movements that have been demonstrated on the San Andreas and other major faults of the region, (b) Reid's elastic rebound theory of strain accumulation and relief (1910), and (c) Louderback's suggestion (1942, p. 312) that the elastic rebound theory can become applicable only at depth, beneath the gouge zone, where even the sheared rock (mylonite) becomes strong enough to permit the building up of strain. Ferguson and Willis (1924) suggested that right-lateral movements between basement blocks produced marginal rows of anticlines, arranged en echelon where shearing was incomplete in the overlying sediments, but with axes parallel to the faults where shearing was complete. The discovery of deformed basement cores in the anticlines seems to require a somewhat different mechanism, but one whose actuation is not immediately apparent.

Unconformities. Unconformities are characteristic of both the marginal shelves of the basin and the adjacent mountain blocks. The first large unconformity above the top of the bedrock complex marks the division between Mesozoic and Cenozoic time. In the Santa Ana Mountains gently folded Cretaceous rocks that may have had east-trending axes are truncated by an unconformity, and are overlain by continental deposits of early Paleocene age.

The most spectacular unconformity in the sedimentary series is middle Miocene in age, although it apparently does not everywhere appear at the same horizon. In the Santa Monica Mountains the upper Miocene Modelo strata overlie middle Miocene Topanga sandstone with a 90° difference in attitude. In the San Joaquin Hills (fig. 4), the middle Miocene San Onofre breccia is bracketed by unconformities. The breccia lies unconformably across planed-off fault blocks, from one of which a probable thickness of 3,500 feet of earlier middle Miocene Topanga sediments had been removed by erosion before the San Onofre was deposited (structure section IJK). The Monterey shale in its turn lies unconformably on all the earlier Miocene rocks. In the Palos Verdes Hills the late middle Miocene Monterey shale and interbedded breccia of San Onofre type lie unconformably on Catalina schist.

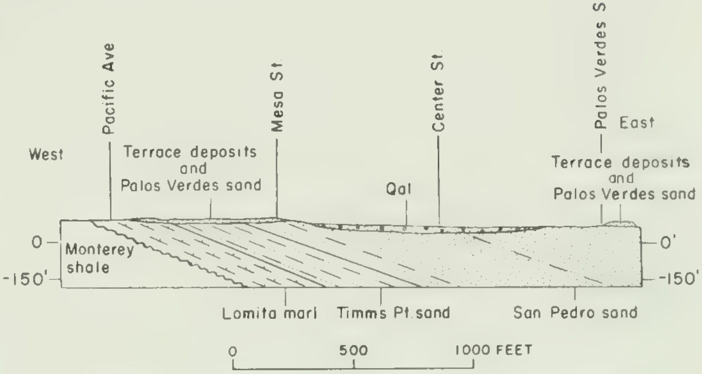

FIGURE 7. Structure section along Second Street, San Pedro.

One of the great surprises from the subsurface exploration of the east side of the Los Angeles basin was the discovery of the Anaheim nose, an anticline in Topanga and older rocks that has west-northwest trend and plunge. The upper Miocene and lower Pliocene sedimentary strata pinch out against this anticline, and upper Pliocene and Pleistocene strata lie with great unconformity across it. Just south of Anaheim these upper Pliocene and Pleistocene strata are 4,500 feet thick. The southeast extension of the Anaheim nose, near the town of Tustin, is marked by Pleistocene or Recent alluvium lying unconformably upon Sespe-Vaqueros and Upper Cretaceous strata. Probably the Anaheim nose began to develop long before the middle Miocene diastrophism, and then was affected by it.

The last period of notable deformation apparently was made up of two episodes, one during late Pliocene or at the end of Pliocene time and the other during middle Pleistocene time. Perhaps the best evidence is exposed at San Pedro (fig. 7). Here the greater hiatus is

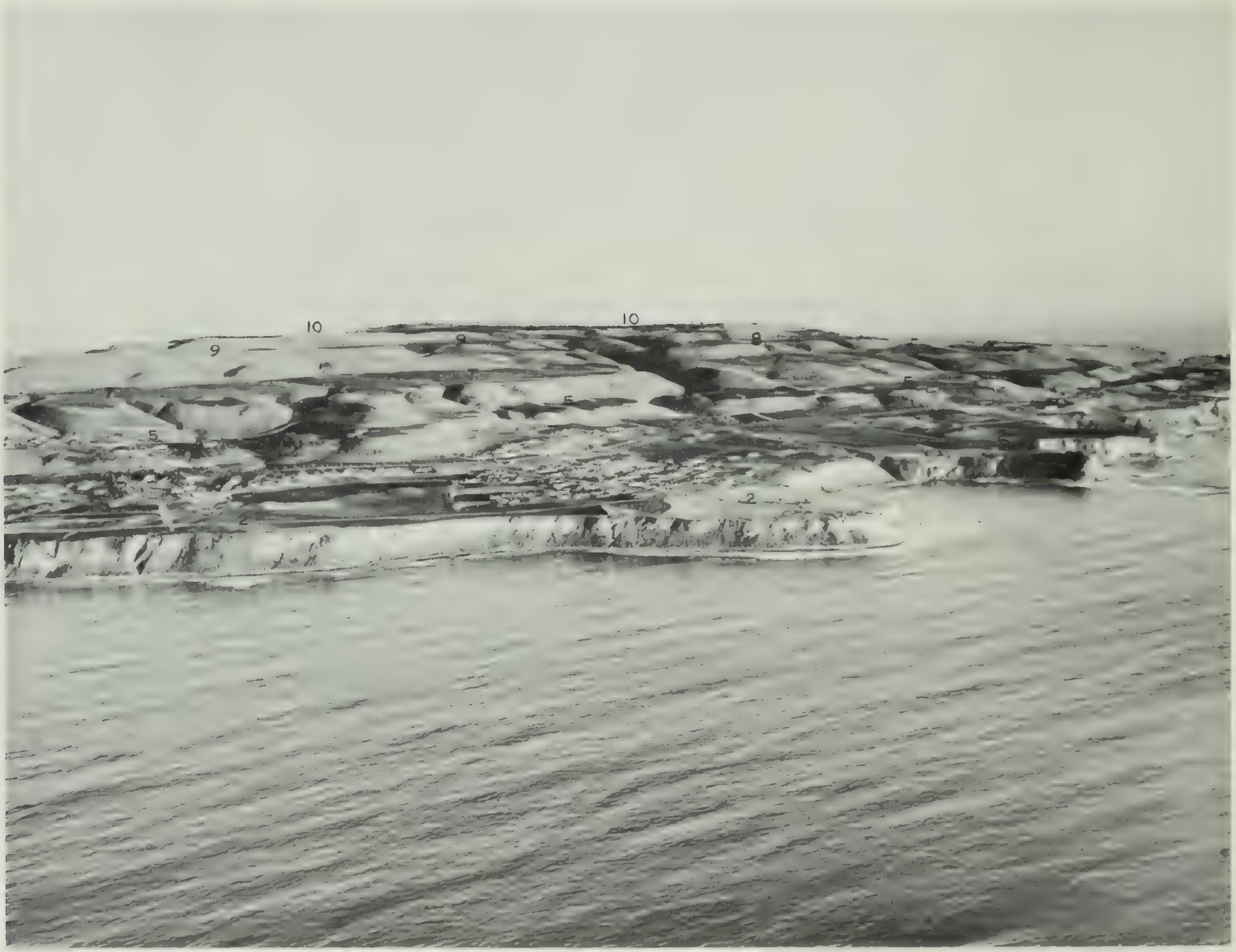

FIGURE 8. Aerial view of late Pleistocene terraces on Palos Verdes Hills, from the west. Terraces numbered as by Woodring et al., 1946. *Photo by J. S. Shelton and R. C. Frampton.*

between Monterey shale (Miocene) and Lomita marl (Pleistocene), but elsewhere in the Palos Verdes Hills the lower Pliocene section is nearly conformable with the Monterey, and in other marginal parts of the basin the Miocene, Pliocene, and early Pleistocene sections are all roughly conformable and all highly folded, with nearly horizontal upper Pleistocene continental formations deposited across their beveled edges. This relationship is especially clear in the gorge of San Jose Creek, at the northwest tip of the Puente Hills.

There is abundant evidence that this latest, essentially Quaternary period of deformation is continuing at the present time. The Capistrano earthquake of 1812 and the Long Beach earthquake of 1933 provide evidence of this activity. Widespread subsidence is indicated by the repeated leveling of the U. S. Coast and Geodetic Survey, which shows that Santa Ana sank 1.568 feet between 1920 and 1946, and that central Long Beach (Anaheim Street at Newport Street) sank 0.768 foot between 1926 and 1946. Much the greatest subsidence, with a maximum sinking of 18 feet between 1933 and 1953, has been limited to the Wilmington oil field and is no doubt related to the removal of oil and gas (Gilluly and Grant, 1949; see also Grant, Contribution 3, Chapter X), although the limitation of extreme subsidence to this one oil field is puzzling. Some, but probably not all, of the lesser but more widespread subsidence may be caused by removal of ground water.

The Los Angeles basin is an area of negative gravity anomalies. In general, the negative Bouguer anomalies become greater toward the northeast, in conformity with the regional gradient. For example, the following results are reported in U. S. Coast and Geodetic Survey Special Publication 244 (1949), with the stations arranged in order from southwest to northeast:

				Gals.		Anomalies (Uncorrected for station elevation)	
Number	Place	Year	Elev.	Observed	Theoretical	Free-air	Bouguer
245	Redondo	1916	23.2 m	979.618	979.648	—.023	—.025
244	Long Beach	1916	8.2	979.619	979.642	—.021	—.021
66	Compton	1910	19.8	979.591	979.652	—.055	—.057
246	Burbank	1916	186.5	979.593	979.677	—.026	—.046
314	Pasadena	1924	228.6	979.577	979.673	—.025	—.049
315	Mt. Wilson	1924	1,719.4	979.253	979.680	+.103	—.060
1023	Pomona	1939	253.4	979.548	979.6667	—.040	—.068
243	Pomona	1916	258.2	979.549	979.666	—.037	—.066
242	Highland	1916	392.6	979.479	979.672	—.072	—.113

When the regional gradient is removed, the residual negative anomalies are greatest in the center of the basin. This is even suggested by the data given above. Compare the —57 milligals at Compton, near the center of the basin, with the —21 milligals at Long Beach, near the southwest margin, and with the —49 milligals at Pasadena, near the northeast margin.

Whether or not Pleistocene and Recent subsidence in the Los Angeles basin is in response to isostatic adjustments cannot be decided without more detailed knowledge of the gravity anomalies indicated by the data given above. No detailed gravity map of the basin has been published.

GEOMORPHOLOGY

Block Units. The primary land forms of the Los Angeles basin are the same mountain and basin blocks that are the principal elements in the structure. The elevated blocks are scored by canyons, the larger of which are bordered by erosional terrace benches, commonly alluvium-covered. The lowland blocks are mostly covered with continental sediments, many of which are present as compound alluvial fans. Deformation, especially at and near the margins of the major blocks, complicates the geomorphology and makes generalization difficult. Some of the larger elevated blocks are marked by widespread erosion surfaces that cut across the structure.

Terraces. The number and elevations of the stream terraces vary from block to block. In the Santa Ana Mountains four sets of terraces are present along the larger streams. On upper Santiago Creek these are 20, 120, 220, and 320 feet above the stream.

Coastal marine terraces in the Palos Verdes Hills number as many as 13, and the highest of these is as much as 1,300 feet above sea level, as described in a previous section.

Antecedent Streams. The principal streams that cross the Los Angeles basin area have cut through rising structural blocks that subdivide the Miocene basin into present-day topographic basins. One clear example is the gorge of San Jose Creek, where it cuts through the northwest tip of the Puente Hills just before emptying into the San Gabriel River. This northwest tip of the Puente Hills is mantled with upper Pleistocene red alluvium, the San Dimas formation, which has been deformed into a flat, northwest-plunging anticline. Almost equally clear are the trenches cut by Aliso Creek and the Santa Ana, San Gabriel, and Los Angeles Rivers in the coastal hills and ridges between Capistrano and San Pedro. The Los Angeles River has maintained two outlets, one into Los Angeles Harbor south of the Palos Verdes Hills and the other through Ballona Slough to Playa del Rey, which is 12 miles north of these hills. In very late Pleistocene time the Santa Ana, San Gabriel, and Los Angeles Rivers cut trenches through the coastal ridge to depths that are now 120 to 180 feet below sea level (Poland et al., 1945). These trenches, which extended inland across the modern basin, have been filled with alluvium but are not known to have been appreciably deformed.

Probably the Santa Ana River, San Gabriel River, and other streams are antecedent to the formation of the Santa Ana Mountains and the Puente Hills, and have maintained their courses as this highland area was uplifted. Coyote Pass in the Repetto Hills and Brea-Tonner Canyon in the Puente Hills are examples of wind gaps.

Surfaces of Deposition and Erosion. Each major stream builds an alluvial fan where it enters a basin. Each fanhead is marked by a stream trench, 10 to 200 feet deep at the canyon mouth and fading out below (Eckis, 1928). Not only do the major streams swing back and forth across their fans, destroying the earlier fanhead surfaces and cutting new ones at lower gradients, but they also bevel the crests of rising anticlines. An example of this is the planing off of the Santa Fe Springs anticline by the San Gabriel River.

Some anticlines, such as Dominguez and West Coyote, have risen more rapidly than the pre-existent streams could erode them, but the records of the truncations have been preserved in their smooth domed surfaces, "Primärrumpfe" in the expressive terminology of Penck (1920, p. 367; Davis, 1932, p. 419). The new radial ravines developed on such hills form consequent drainages and give evidence for the doming, as was pointed out by Vickery (1928).

More widespread erosion surfaces have been developed east of the Los Angeles basin and the Santa Ana Mountains, both on resistant crystalline blocks and on the upper Tertiary and Quaternary continental and marine sediments that were deposited on intervening depressed blocks. The two most extensive inland surfaces are about 1,700 and 2,100 feet above sea level (Dudley, 1936). The lower of these may extend into the area here considered, dropping to altitudes of 1,200 or even 1,000 feet near the sea. Well-marked examples are shown in figure 6, on the Puente Hills (foreground) and the foothills of the San Gabriel Mountains (middle distance). The intervening lower blocks may have dropped relatively, without much change in the positions of the uplands. On the other hand, the accordance of the Puente Hills and other summit levels may be a matter of chance. The age of these old surfaces must be Quaternary and perhaps late Pleistocene, but much has happened since their formation, including the deposition and weathering of upper Pleistocene continental formations.

CONCLUSIONS

The sedimentary rocks above the great Mesozoic unconformity in the Los Angeles basin area can be compared with the flysch and molasse of the Alps. Tens of thousands of feet of clastic sediments are concentrated in a small area. Central conformity is the rule and marginal unconformities are common.

The Upper Cretaceous to lower Miocene rocks are mostly shallow marine or continental deposits, especially in the Santa Ana Mountains. The marine strata contain fairly numerous shallow-water mollusks, echinoids, and other invertebrates. Some Cretaceous strata, and especially the Holz shale member of the Ladd formation, may be deep-sea deposits, as they lack shallow-water fossils.

The late Miocene sediments may be bathyal, and the early Pliocene sediments may be mostly deep-sea deposits. The absence of shallow-water megafossils, the presence of a few Recent bathyal Foraminifera in the Miocene, many characteristic deep-water Foraminifera in the Pliocene, and the frequency of depositional structures suggesting turbidity currents all point to deposition in deep water.

Some doubt remains as to these general conclusions, and many details are most uncertain. For example, the origin of the San Onofre breccia is now problematical. Thirty years ago it could be asserted with confidence that the earthy portion of the breccia, which is made up exclusively of material of western origin, uncontaminated even by grains of orthoclase or flakes of biotite, must have been deposited on the eastern slopes of Catalinia as material of continental origin. We still consider this origin probable for the main portion of the San Onofre. An example is the red and gray earthy breccia at Dana Point, near Capistrano, where the few and fragmentary marine fossils may merely indicate minor shore deposits. But west of Dana Point, higher in the section, sandy San Onofre breccia and conglomerate, with oysters and pectens, are slightly contaminated with sand of eastern origin, and seem surely the products of marine and probably of shallow-water deposition. The overlying Monterey shale may be an upper bathyal deposit, in which case the great enclosed lens of gray earthy schist breccia, exposed on the beach and in the sea cliffs (fig. 5), may be a mass that slid into a moderately deep sea. The schist-breccia portion of the coarse clastic lens is nearly mono-lithologic. The easiest explanation of such a peculiar sediment is the breaking away of the forward portion of an overthrust block, possibly even a flat sheet or nappe.

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6. GEOLOGY OF THE TRANSVERSE RANGE PROVINCE, SOUTHERN CALIFORNIA[*]

By Thomas L. Bailey [†] and Richard H. Jahns [‡]

GENERAL FEATURES

The Transverse Range province of southern California is an elongate geomorphic and structural unit that trends essentially east-west across parts of Santa Barbara, Ventura, Los Angeles, San Bernardino, and Riverside Counties (pl. 4). Its name reflects its transverse orientation with respect to the adjacent provinces, especially the Coast Ranges and Sierra Nevada to the north and the Peninsular Ranges to the south. This distinctive province is geologically very complex, and comprises chains of mountains and hills that are flanked or separated by narrow to moderately broad valleys. These features, as well as most of their structural elements, lie athwart the general northwest-southeast grain of southern California, and several of them are responsible for the anomalous east-west alignment of the coast from Point Conception to the Santa Barbara area, and along the north side of Santa Monica Bay.

The Transverse Ranges extend from the most westerly part of the southern California coast, where the Santa Ynez Mountains plunge under the Pacific Ocean at Point Arguello, to the eastern end of the Little San Bernardino Mountains, in central Riverside County, and even to points beyond. On the basis of major structural features, the inland end of the province can be placed at the eastern edge of the Eagle Mountains, or only about 50 miles from the Colorado River. Thus the total length of the Transverse Ranges exposed above sea level is about 300 miles. The province is about 50 miles wide at its western end, as measured between the Santa Ynez River and the Channel Islands southwest of Santa Barbara; as much as 55 miles farther east, as measured between Tejon Pass and Santa Monica Bay; only 15 miles in the Cajon Pass area, where the San Andreas fault zone separates the San Gabriel and San Bernardino Mountains; as much as 30 miles in the middle part of the San Bernardino Mountains; and 20 miles or less in the areas farther east (pl. 4).

The province is characterized by great topographic contrasts, and includes much of the highest ground in southern California. It is divisible into thirteen well-defined topographic and geologic units, which can be described, in a general west-to-east direction, as follows:

1. The *Santa Ynez Mountains* extend eastward from Point Arguello to the Ventura River, a distance of 80 miles. Their crest height ranges from 1,500 feet to 4,800 feet. They consist mainly of sedimentary rocks that are Cretaceous to Quaternary in age.
2. The *Topatopa Mountains* are an easterly and wider continuation of the Santa Ynez Mountains, and extend to lower Sespe Creek, north of Fillmore. Here they give way to the *Piru Mountains*, which terminate against the San Gabriel fault north of Castaic (pl. 4). The combined length of these two ranges is approximately 36 miles, and much of their crest line is 3,500 feet to 6,700 feet in altitude. They are underlain chiefly by sedimentary rocks of early and middle Tertiary age.
3. The *Channel Islands* and *Santa Monica Mountains* form a range that is at least 125 miles long and 3 to 12 miles wide. It terminates eastward at the Los Angeles River. Much of the range has altitudes of 500 feet to 3,000 feet; a large part of the remainder, in contrast, lies beneath the Pacific Ocean. It is composed mainly of Cretaceous to Miocene sedimentary and volcanic rocks. Older crystalline rocks appear in the eastern part of the Santa Monica Mountains and on Santa Cruz Island.
4. *The Pine Mountain-Frazier Mountain interior ranges* form a 12- to 25-mile wide complex group of short, high, and rugged subparallel ridges of sedimentary rocks, as well as still higher and less elongate granitic mountain masses. These lie between the San Rafael Mountains on the northwest and the Santa Ynez and Topatopa Mountains on the south, and they are terminated on the northeast by the San Andreas and associated faults. The tops of the sedimentary ridges rise to elevations of 5,000 feet to 7,400 feet above sea level, and the tops of the granitic mountains have elevations of 6,000 to 8,800 feet.
5. The *Ventura basin* lies between the Santa Ynez and Topatopa Mountains on the north and the Santa Monica Mountains and Channel Islands on the south. It contains several intra-basin chains of hills and mountains that in general are anticlinal. They rise from 400 feet above sea level to as much as 3,700 feet in the Santa Susana Mountains. Between these intra-basin highlands are broad-bottomed synclinal lowlands, the Ojai, Santa Clara, and Simi Valleys. Two of the ranges, Oak Ridge and Camarillo Hills, die out at their west ends into the flat, alluviated Oxnard Plain, which is the most extensive lowland in the Ventura basin. The western half of the basin is occupied by an epicontinental sea, the Santa Barbara Channel. The Ventura basin, including the submerged portion, is about 120 miles long and 20 to 40 miles wide. Its axial portion is marked by the valley of the Santa Clara River (fig. 4).
6. The Ventura basin is bounded on the east by the San Gabriel fault, beyond which lies the *Soledad basin*. This elongate basin is flanked on the south by the San Gabriel Mountains, and terminates eastward against the San Andreas fault zone. Both the Ventura and Soledad basins contain thick sections of marine and nonmarine strata of Cenozoic age, but the history and conditions of sedimentation appear to have been so different on opposite sides of the San Gabriel fault that the two basins are best regarded as separate units.
7. The *Ridge basin* lies north of the eastern end of the Ventura basin, and is bounded on the southwest by the San Gabriel fault, on the north by the San Andreas fault, and on the east by the Liebre Mountains and Sierra Pelona. It trends northwest, and is about 20 miles long and 2 to 8 miles wide. It is distinguished by an enormously thick section of dominantly nonmarine strata of Pliocene and late Miocene age, and its history evidently was quite different in many respects from those of the nearby Ventura and Soledad basins.
8. The *Liebre Mountains* and *Sierra Pelona* are en-echelon ranges that lie between the Mojave Desert on the north and the Soledad basin on the south. They are separated from the Topatopa Mountains by the Ridge

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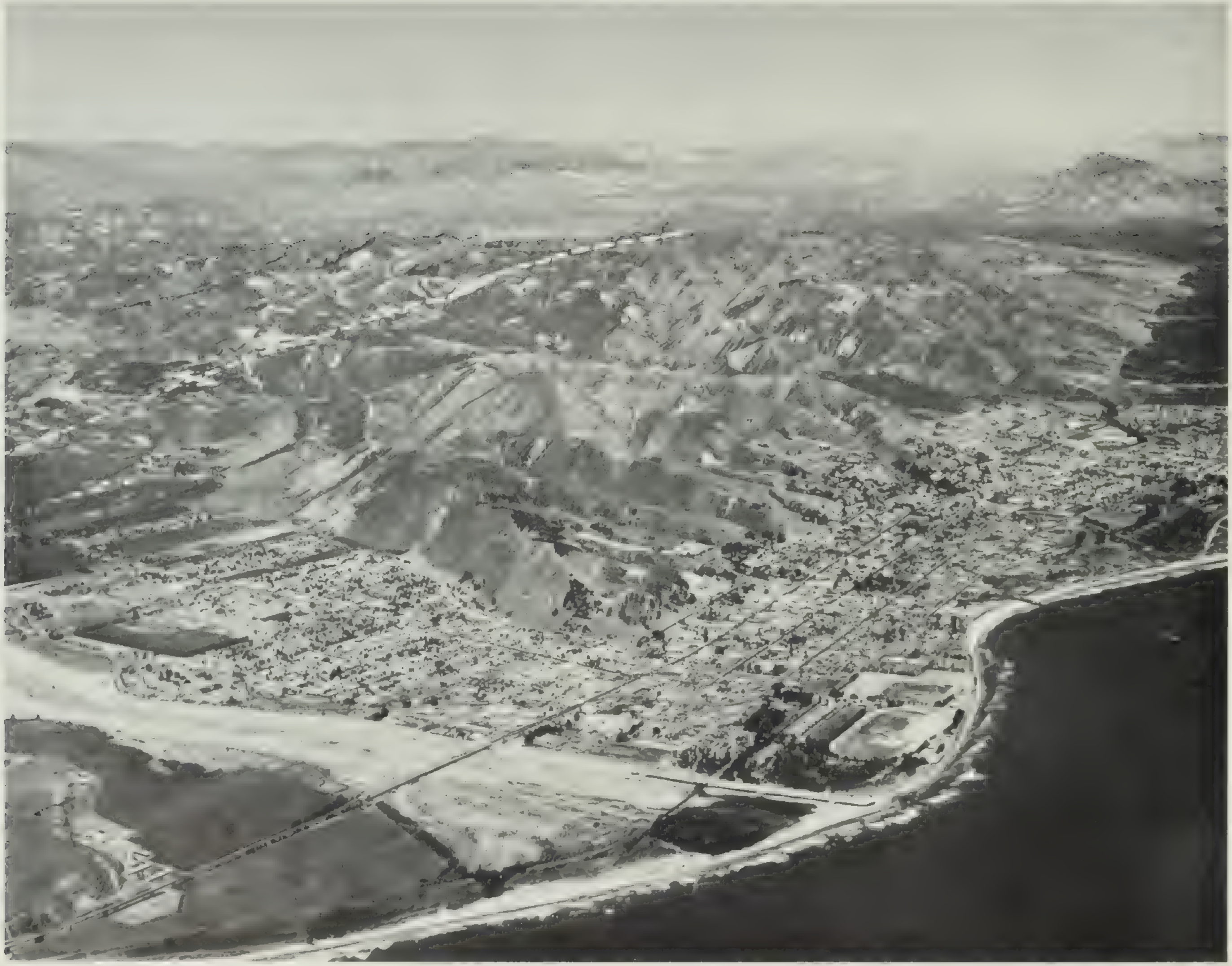


Figure 1. View east-northeast toward central part of Ventura basin, from Ventura (foreground). Ventura River is in middle and left foreground, and Santa Clara River valley is at right and in distance. Topatopa Mountains form the skyline at left. Hills in center of view consist of marine Pliocene and lower Pleistocene strata on the south flank of the Ventura anticline, the axial trace of which is shown approximately by the dashed line. *Pacific Air Industries photo.*

basin, and terminate eastward against the San Andreas fault zone. In most places they rise to altitudes of 3,000 feet to 5,800 feet. Unlike most of the ranges farther west, they consist almost entirely of igneous and metamorphic rocks that are pre-Cenozoic in age.

9. The *San Gabriel Mountains* form a bold, high mass that extends from the east end of the Ventura basin near Newhall to Cajon Canyon northeast of San Bernardino (fig. 3), a distance of about 60 miles. This range is lens-shaped in plan, and rises to general altitudes of 5,000 to 9,000 feet. Its highest point, the summit of San Antonio Peak, is 10,080 feet above sea level (fig. 2). The range is bounded on all sides by major faults, and is composed of plutonic igneous rocks of late Mesozoic age, together with a very complex series of older plutonic, metasedimentary, and metavolcanic rocks.

   The *Verdugo Mountains* and *San Rafael Hills* form a ridge, 15 miles long and 3 miles wide, that apparently is an upfaulted sliver of crystalline rocks along the south side of the western San Gabriel Mountains (fig. 4). This ridge forms a part of the east boundary of the San Fernando Valley, northeast of Los Angeles.

10. The *San Fernando Valley*, a broad plain about 10 miles by 20 miles in its elliptical plan, lies between the western San Gabriel Mountains and the eastern Santa Monica Mountains (fig. 4). This plain or sub-basin is an en-echelon offshoot from the southeastern part of the Ventura basin, and beneath the alluvium on its floor is a complex section of Cenozoic and upper Mesozoic sedimentary rocks.

11. The northern third of the *Los Angeles basin*, which adjoins much of the San Gabriel Mountains on the south, includes the thickly alluviated San Gabriel Valley and the intra-basin Repetto and San Jose Hills along the southern margin of this valley. Most of this area is underlain by sedimentary and volcanic rocks of middle and late Tertiary age. Although other east-trending low ranges, such as the Coyote Hills, are present farther south in the Los Angeles basin, most of the structural elements in the central and southern parts of this basin have a northwest alignment and hence represent the northern end of the Peninsular Range province.

12. The *San Bernardino Mountains* extend eastward from Cajon Pass for a distance of 55 miles, and in general rise to altitudes of 5,000 feet to 11,000 feet. They are distinguished by deep and steep-walled canyons, a subdued upland surface that is markedly discontinuous, and several prominent peaks and ridges that include San Gorgonio Peak, whose summit (altitude 11,485 feet) is the highest point in southern California (fig. 14). The east end of these mountains is marked by Morongo Valley, which separates them from the Little San Bernardino Mountains farther east.

    A zone of profound disturbance, defined mainly by the San Andreas and San Jacinto faults, separates the San Bernardino Mountains from the San Gabriel Mountains to the west (fig. 3). The geology of the two ranges is similar in many respects, but metamorphosed sedimentary rocks of Paleozoic age are more abundant in the San Bernardino Mountains. These strata rest upon a complex assemblage of older, more severely deformed rocks, and are cut by widespread plutonic rocks of Mesozoic age.

13. The *Little San Bernardino Mountains*, *Pinto Mountains*, and *Eagle Mountains* are desert ranges in a belt that extends eastward from Morongo Valley for a distance of about 70 miles. They range in altitude from 3,000 feet to 5,400 feet. They are composed mainly of Mesozoic plutonic rocks that contain numerous septa and inclusions of older metamorphic rocks, and some very large masses of these older rocks also are present.

The climate in much of the Transverse Range province is semiarid, but it ranges widely from subhumid and humid in the higher parts of the San Gabriel and San Bernardino Mountains to truly arid at the eastern end of the province. The higher peaks in the San Bernardino and San Gabriel Mountains usually are snow-capped during much of the year (fig. 2), and snow frequently lasts through the winter months in the Pine Mountain-Frazier Mountain interior ranges and in the higher parts of the Topatopa Mountains. In most of the region the annual rainfall ranges from 12 to 20 inches, and nearly all of it falls during the period from November to March, inclusive.

The topography in much of the region represents late youthful to early mature stages of the erosion cycle, and sharp, rugged ridges and narrow, steep-sided, deeply incised valleys are characteristic. Most of the streams are intermittent, and generally flow only during the winter and spring seasons. An apron of large alluvial fans is a prominent physiographic feature of the oversteepened south front of the San Gabriel Mountains (fig. 2), and many well-developed fans and pediments also are present on the north slopes of this range, as well as on the flanks of the San Bernardino Mountains and the desert ranges to the east.

The geology of large parts of the Transverse Range province has been described by several investigators, notably Dibblee (1950), Hill (1928), Kew (1924), Miller (1934), Reed (1933), Simpson (1934), and Vaughan (1922). Many descriptions and discussions of smaller areas and specific features or problems also have been published, and a sampling of these is included in the list of references at the end of this paper. The region contains numerous marine and nonmarine terraces, upland surfaces of low relief, fault-controlled valleys and canyons, and other physiographic features that raise interesting problems, but most of these are noted elsewhere in this volume (see especially Sharp, Contributions No. 1 and No. 3, and Putnam, Contribution No. 7, Chapter V), and hence are not discussed in this paper.

THE GEOLOGIC SECTION: OLDER ROCKS

General Relations. As indicated in the foregoing resumé, the Transverse Range province varies tremendously in its exposed lithologic components, which are shown in generalized form in plate 4. As in other parts of southern California, the geologic section is readily divisible into two main parts that are separated by a profound unconformity. This break, and the marked contrasts between the rocks that lie above and beneath it, reflect a major episode of Mesozoic diastrophism, igneous intrusion, and metamorphism.

The oldest rocks above the unconformity are marine strata of Upper Cretaceous age, and in some places the rocks beneath it are mildly metamorphosed strata that may well be as young as Cretaceous. In the eastern part of the Transverse Range province, the

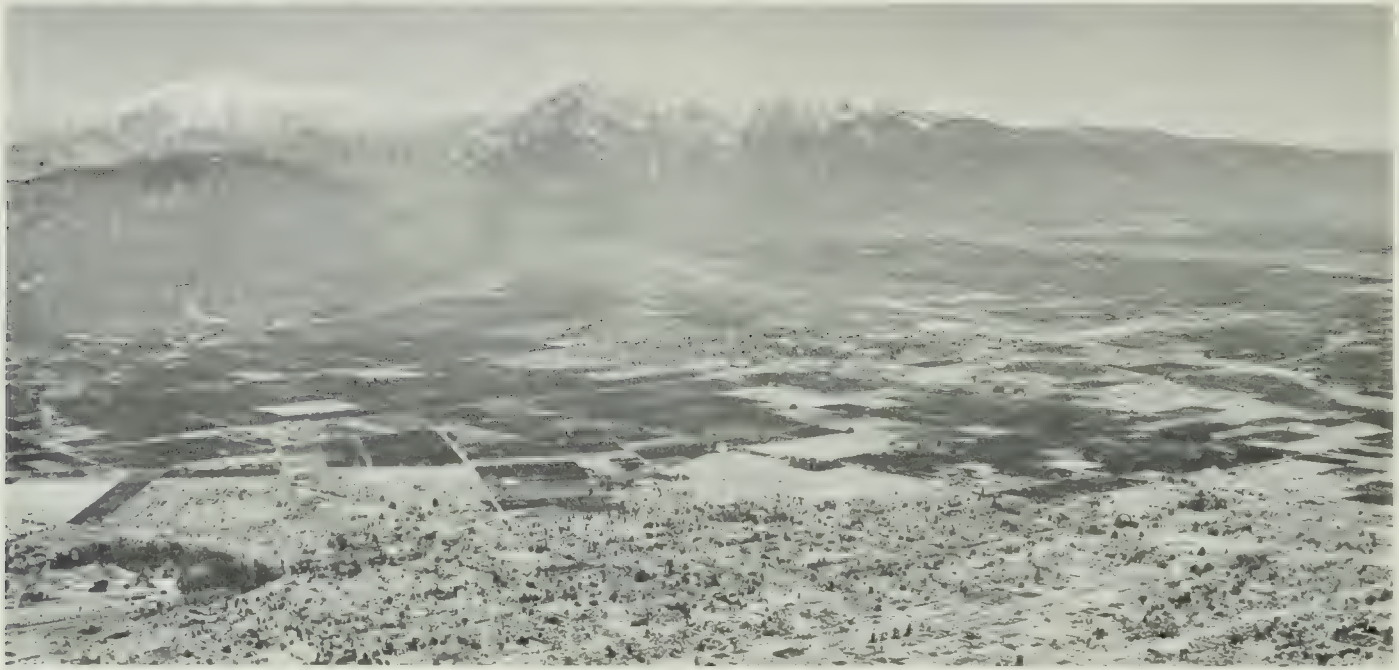


FIGURE 2. View northeast toward scarp of San Gabriel Mountains, from Pomona (foreground). The three main peaks are, from left to right, San Antonio Peak, Ontario Peak, and Cucamonga Peak. San Bernardino Mountains form the skyline at right. The large alluvial fan in central part of view heads at the mouth of San Antonio Canyon; the course of this canyon marks the trace of a major zone of transverse faulting. *Photo courtesy Fairchild Aerial Surveys, Inc.*

exposed rocks are almost wholly igneous and metamorphic types of pre-Cambrian to Cretaceous age, and hence are members of the older sequence. Similar rocks are present in the western part of the province, but in most of the ranges and basins there they are concealed beneath thick sections of Cretaceous, Tertiary, and Quaternary clastic sedimentary rocks.

Most abundant and widespread in the sequence that lies beneath the great unconformity are plutonic rocks, mildly to severely metamorphosed sedimentary and volcanic rocks, and complex assemblages of migmatitic gneisses. These rocks, referred to collectively as ''basement,'' ''basement complex,'' or ''crystalline basement'' by many geologists, bear testimony to a highly involved series of events that probably began in pre-Cambrian time and culminated with development of batholithic masses of plutonic rocks in late middle or even late Mesozoic time.

The Western Ranges. In the Santa Ynez Mountains basement rocks are exposed only in a few small areas near the northern margin of the range. They consist of slightly metamorphosed but highly folded and faulted arkosic sandstones, slaty shales, and radiolarian cherts that have been intricately invaded by masses of serpentine and other basic intrusives. These rocks are a part of the Franciscan group, and probably are of Jurassic age.

Beneath the sedimentary strata of the Topatopa Mountains are granodiorite and related plutonic rocks of Jurassic or Cretaceous age, which enclose some roof pendants of older gneiss. These rocks are extensively exposed in areas to the north, and Frazier Mountain and Mount Pinos, for example, are underlain chiefly by quartz diorite, granodiorite, and a variety of migmatitic gneisses. The Sierra Pelona and the high northern part of the Liebre Mountains consist mainly of schists and gneisses that have been intruded by large bodies of granitic rocks. The oldest recognizable unit in this basement terrane is the Pelona schist, a thick sequence of quartz-mica schist, actinolite-mica schist, and chlorite-rich schists with minor beds of interlayered quartzite, marble, and amphibolite. Most of these rock types are fine grained, but in places they are closely associated with coarse-grained, highly deformed gneisses and migmatites. They probably are pre-Cambrian in age (Simpson, 1934, pp. 380-381). Sediments of presumably Paleozoic age are represented by hornfels, schist, and marble that occur mainly as pendants and inclusions in younger plutonic rocks.

The core of the Santa Monica Mountains and Channel Islands comprises several thousand feet of mildly metamorphosed argillaceous rocks and numerous younger intrusive masses of granitic to quartz dioritic composition. The dominant rock type in the metamorphic sequence has been variously termed argillite, phyllite, and slate, and in places it grades into mica and chlorite schists. It is lithologically similar to rocks of known Triassic age in the Santa Ana Mountains to the southeast, and is fundamentally different in composition and texture from mildly metamorphosed argillaceous rocks that crop out in the Palos Verdes Hills and on Catalina Island to the south (see Woodford, et al., Contribution No. 5, this chapter).

The Eastern Ranges. The San Gabriel Mountains are composed of a wide variety of crystalline rocks whose origin and age relations are not yet fully understood. An older sequence, of probable pre-Cambrian age, is represented in the northeastern part of the range by the Pelona schist (Noble, 1927), and elsewhere in the range by a complex and highly deformed assemblage of gneiss, schist, quartzite, marble, and numerous hybrid rocks, in part termed the San Gabriel formation by Miller (1934, pp. 49-56). Recent investigations near the western end of the range have demonstrated, by means of analyses of clean zircon concentrates, that at least two kinds of plutonic rocks there are pre-Cambrian in age (Neuerburg and Gottfried, 1954).

Of particular interest in the western third of the range is a gabbroic complex that includes anorthosite, norite, various transitional rocks, and apatite-ilmenite rocks (Miller, 1931; Higgs, Contribution No. 8, Chapter VII, this volume). The anorthosite is composed almost entirely of andesine. It has been thoroughly shattered and extensively sheared on a wide range of scales, and it contains numerous dikes and inclusions of other rock types (fig. 5). It characteristically weathers chalky and white, and commonly forms ridges and slopes that are fairly smooth in detail (fig. 11).

A younger sequence of rocks in the San Gabriel Mountains includes argillite, phyllite, quartzite, some marble, and several volcanic types. Some of the strata probably are correlative with fossiliferous upper Paleozoic rocks in the San Bernardino Mountains to the east, whereas others may well be Mesozoic in age. Still younger is a group of widespread plutonic rocks that range in composition from diorite to granite, and that probably are Jurassic or Cretaceous in age (Miller, 1934, pp. 61-65; Simpson, 1934, p. 384; Woodford, 1939, p. 257). In most parts of the range both these and the older rocks have been shattered and sheared to an impressive degree, and numerous zones of mylonite have been recognized (Alf, 1948). Many of the rocks are interlayered or otherwise intimately mixed (fig. 6), and the igneous rocks commonly contain abundant inclusions. Both the igneous and the metamorphic rocks are transected by dikes of aplite, pegmatite, lamprophyre, amphibolite, and fine-grained basaltic to rhyolitic rocks.

The San Bernardino Mountains are composed mainly of gneisses, schists, plutonic rocks, and several kinds of hybrid rocks, and also contain a sequence of marble, in which fossils of Carboniferous age can be recognized, and older quartzites and carbonate rocks of Paleozoic age (Vaughan, 1922, pp. 352-361; Woodford and Harriss, 1928, pp. 268-271; Guillou, 1953, pp. 3-13). The Paleozoic section appears mainly in the northeastern part of the range, and is about 10,000 feet thick. As in the San Gabriel Mountains, the rocks can be divided into an older sequence, characterized mainly by gneisses and schists of probable pre-Cambrian age, and a younger sequence of Paleozoic and Mesozoic rocks.

Exposed over large parts of the San Bernardino Mountains, Little San Bernardino Mountains, and other mountains to the east are plutonic rocks whose average composition appears to be in the quartz monzonite range. The most widespread type, referred to as the Cactus granite (Vaughan, 1922, pp. 363-374; Woodford and Harriss, 1928, pp. 271-274; Miller, 1946, p. 472), is mainly a light-colored quartz monzonite of Mesozoic age. The lead-uranium ratio of euxenite from a pegmatite body that cuts the Cactus granite about 11 miles southeast of Old Woman Spring, near the northern edge of the San Bernardino Mountains, indicates a middle Jurassic age (Hewett and Glass, 1953, pp. 1047-1050). Both the Cactus granite and other plutonic rocks in the eastern end of the Transverse Range province contain numerous inclusions and septa of metamorphic rocks, and some large areas are underlain by gneisses, schists, amphibolite, quartzite, conglomerate, crystalline limestone and dolomite, and other mildly to severely metamorphosed rocks (Harder, 1912, pp. 19-21) whose sequence and age relations have not been firmly established.

THE GEOLOGIC SECTION: YOUNGER ROCKS

Cretaceous Rocks. Lower Cretaceous (Knoxville) sediments are exposed within the Transverse Range province only in the western

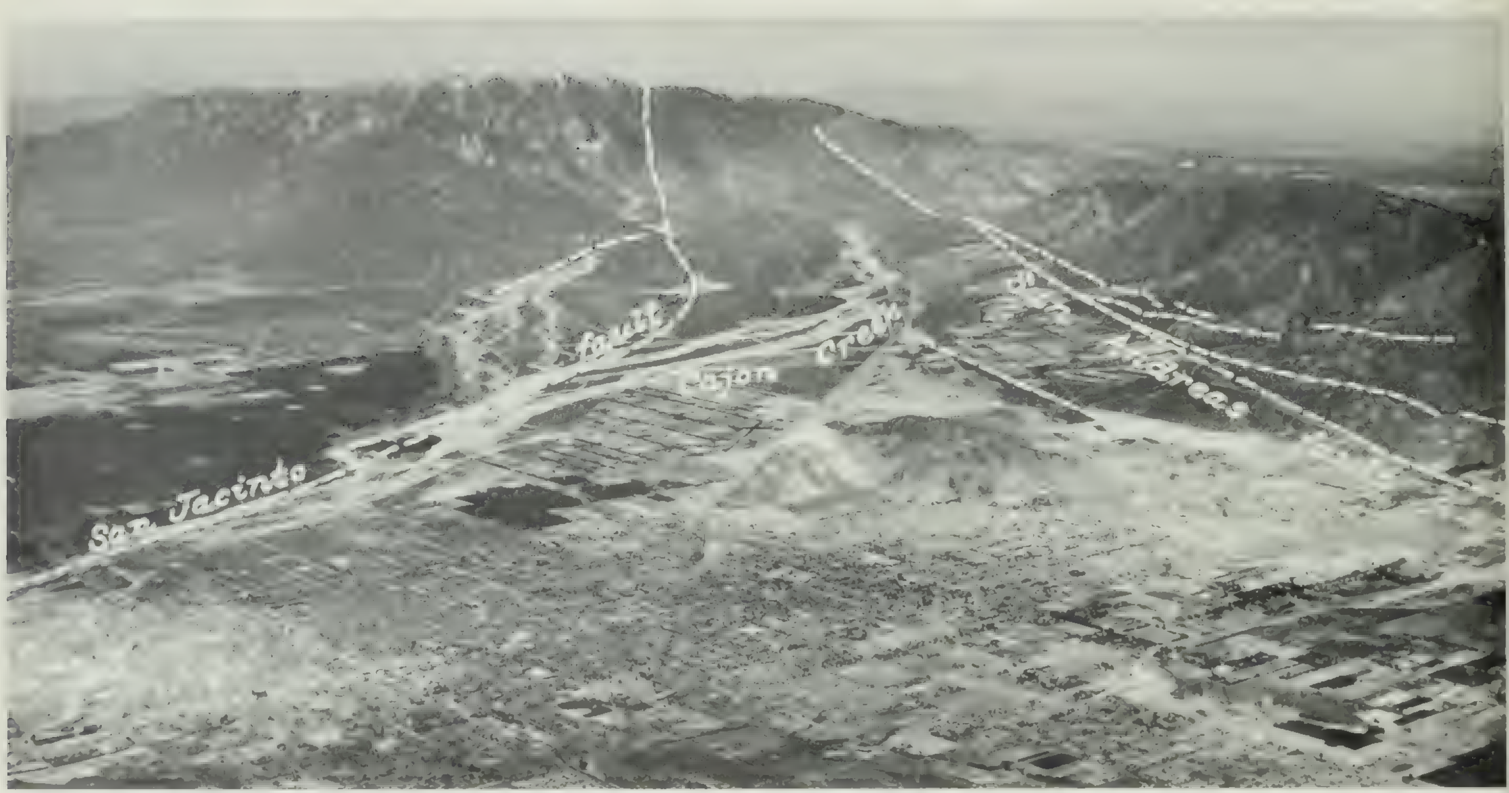


FIGURE 3. View northwest over San Bernardino, showing the San Gabriel Mountains (left) and San Bernardino Mountains (right). San Antonio peak is on skyline at left, and Mojave Desert is in distance at right. Light-colored outcrops in upper drainage of Cajon Creek beyond the trace of the San Andreas fault are terrestrial strata of Miocene age (see fig. 7). Traces of major faults are shown by dashed lines. *Pacific Air Industries photo.*

Santa Ynez Mountains, near Lompoc and Buellton. These consist mainly of considerably sheared marine silty shales that are as much as 7,500 feet thick.

Upper Cretaceous sediments are much more widespread. They crop out extensively in the Santa Ynez Mountains, especially toward the west end of the range. To a lesser extent they appear in the northwestern Topatopa Mountains, where they consist of hard, gray, marine shale with thin beds of sandstone and a few lenses of coarse conglomerate. Similar Cretaceous rocks are widely exposed in the San Rafael Mountains north of the western Transverse Ranges. The Simi Hills and vicinity, in eastern Ventura County, are composed mainly of thick-bedded, northward dipping, marine Upper Cretaceous sandstones.

In the eastern Santa Monica Mountains the Cretaceous section consists mostly of conglomerate beds that are about 3,000 feet thick. Terrestrial redbeds form the lower several hundred feet of the section, but the remainder is marine. No rocks of definitely Cretaceous age have been found in the eastern half of the Transverse Range province, but Upper Cretaceous clastics are widely exposed in the Santa Ana Mountains, a part of the Peninsular Range province that forms the eastern rim of the Los Angeles basin.

Eocene Rocks. Paleocene and lower Eocene sandstone, shale, and conglomerate crop out extensively on the north slopes of the Simi Hills and at the east end of Simi Valley, where their aggregate thickness is 3,500 feet. A thick section of clastic Paleocene strata is exposed along the southern margin of the Liebre Mountains, north of the Santa Clara River valley. In the eastern Santa Monica Mountains about 1,000 feet of Paleocene rocks consists principally of shales with thin lenses of limestone.

Thin, elongate fault slivers of sheared and fractured Paleocene shale, sandstone, and pebbly to cobbly conglomerate are present in the western Santa Ynez Mountains and western San Gabriel Mountains. Larger fault-bounded masses of similar but less deformed rocks occupy parts of the San Andreas fault zone along the northeastern margin of the San Gabriel Mountains (Dickerson, 1914; Noble, Contribution No. 5, Chapter IV, this volume), and further attest the former wide distribution of Paleocene strata.

Sedimentary rocks of middle and late Eocene age form most of the higher parts of the Santa Ynez and Topatopa Mountains, where their thickness ranges from 3,000 feet near Point Conception to more than 13,000 feet north of Ventura. On San Miguel Island 9,000 feet of these Eocene clastics has been reported, but part of them may be Cretaceous in age. The upper and middle Eocene section consists mainly of alternating black shale and hard, gray sandstone. A few beds of conglomerate also are present. The only significant carbonate unit, an orbitoidal limestone (Sierra Blanca) that ranges in thickness from a few feet to a few hundred feet, occurs as lenses at the base of the middle Eocene section in the northern Santa Ynez and southern San Rafael Mountains, where it rests unconformably on Cretaceous rocks. Zones of red shale alternate with oyster-bearing sandstone (Coldwater sandstone) in the upper 2,500 feet of the Eocene section between Santa Barbara and Fillmore.

An upper Eocene continental redbed series (lower part of Sespe formation) crops out in the Simi Valley region, and has been penetrated in oil borings on South Mountain and Oak Ridge, south of Fillmore (fig. 8). These strata contain a large fauna of land vertebrates including early primates, rhinoceroses, titanotheres, and numerous rodents (see Durham, et al., Contribution No. 7, Chapter III). They are lithologically indistinguishable from overlying Oligocene (Sespe) redbeds with which they have been mapped, and they record the first important marine regression in the Tertiary history of this region.

The Eocene sands commonly are tight, but they produce oil commercially in several parts of the Ventura basin.

Oligocene Rocks. The Oligocene section is characterized by a generally thick succession of redbed sandstones, silty shales, and conglomerates of the Sespe formation, which extends from an area a few miles east of Point Conception eastward to the southern Liebre Mountains northeast of Saugus, and probably southeastward to Santa Ana Canyon at the east end of the Los Angeles basin. Vertebrate faunas indicate that this formation ranges in age from late Eocene through Oligocene to early Miocene. On the south flank of the Santa Ynez Mountains west of Canada Refugio (Refugio Canyon), the basal beds begin to interfinger with marine sandstones and shales. The upper half of the redbed section is overlapped to the west by marine strata of early Miocene age. This transition from continental to marine Oligocene beds continues westward progressively, so that near Point Conception and Lompoc all of the Oligocene section, here about 1,000 thick, contains numerous marine fossils.

Lower Miocene to Oligocene redbeds also occur on Santa Rosa Island and in the Santa Monica Mountains. Angular unconformities that mark local uplifts are present at the top of the Oligocene section in the western Santa Ynez Mountains and in the Simi and Las Posas Hills; elsewhere the Oligocene-Miocene contact is apparently conformable. The Oligocene (and some upper Eocene) redbeds include some of the most important oil reservoir sands in the Ventura basin.

Coarse conglomerate, breccia, and arkosic sandstone, in large part of typical redbed lithology, are widely exposed in the Soledad basin north of the western San Gabriel Mountains (fig. 11), and also appear as discontinuous erosional remnants along the San Andreas fault zone farther east. These nonmarine strata, known as the Vasquez formation, locally reach thicknesses of about 14,000 feet. They are overlain with marked unconformity by other nonmarine strata of early Miocene age, and probably are correlative with at least a part of the Sespe formation to the west. In some parts of the basin the section contains as much as 4,000 feet of andesite and basalt, chiefly in the form of flows.

Miocene Rocks. In the western Ventura basin and Santa Ynez foothills the Miocene section comprises, in upward succession, a basal unit of sandstone and conglomerate 50 feet to 400 feet thick (Vaqueros formation), 1,500 feet of mudstone, 1,000 feet to 2,500 feet of laminated, highly organic (foraminiferal or diatomaceous) shale, shaly chert, and diatomite, and 2,000 feet of silty brown organic shale at the top. Most of this Miocene shale is highly bituminous, and hence constitutes a rich source rock for petroleum. In the eastern part of the Ventura basin, between Fillmore and Saugus, the middle and upper Miocene section becomes progressively more sandy and thickens to 10,000 feet or more east of Piru, where there is a concentration of oil fields producing from these sands.

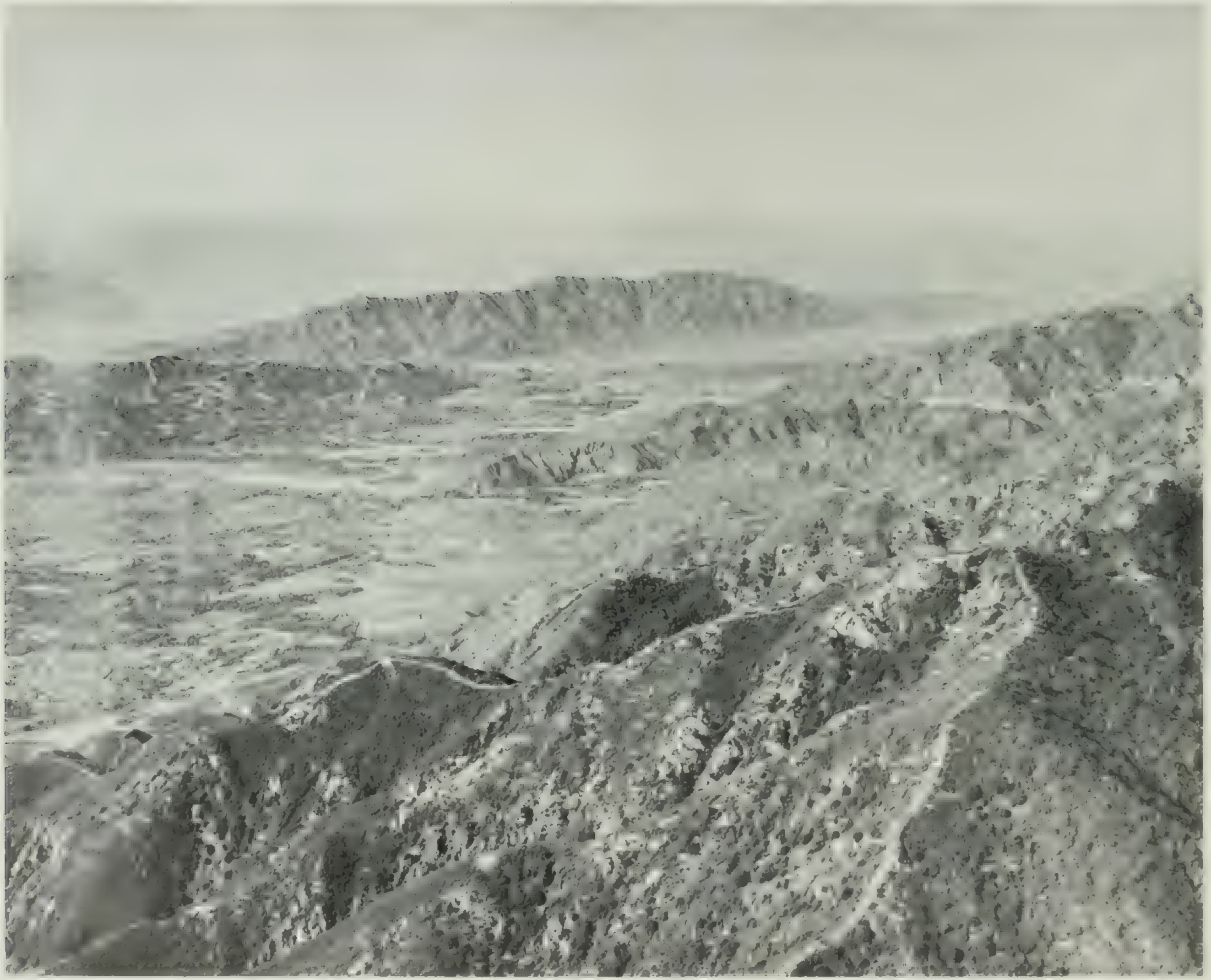


FIGURE 4. View west-southwest from the San Gabriel Mountains toward Verdugo Mountains and the San Fernando Valley beyond. Santa Monica Mountains are in the left distance, and light-colored slopes of the Santa Susana Mountains appear at the far right. *Photo courtesy Fairchild Aerial Surveys, Inc.*

The northern Los Angeles basin contains about 3,000 feet of lower and middle Miocene sandstone and conglomerate, the lower part of which includes a few redbeds. These are overlain by a maximum of 9,000 feet of upper Miocene diatomaceous shale, cherty shale, silty shale, sandstone, and conglomerate. This Miocene succession is similar to that in the eastern Ventura basin, where coarse clastics are interbedded with the organic shale.

During middle Miocene time a deep geosyncline was developed on the site of the present Santa Monica Mountains and Channel Islands. In this rapidly subsiding marine trough was deposited 3,000 to 15,000 feet of middle Miocene clay shale, sandstone, conglomerate, and schist breccia. The thickest section is in the western Santa Monica Mountains. Shortly after their deposition, these sediments were invaded by sills, dikes, and chonoliths of diabase, basalt, and some andesite. Two or three lenses of submarine volcanic flows (trachyandesites, andesites, and basalts) as much as 5,000 feet thick appear in the upper part of the middle Miocene section. Minor extrusion of acid volcanic rocks also occurred during middle Miocene time 100 miles to the northwest, in an area a few miles northwest of Point Conception.

The orogeny that raised up the Santa Monica Mountains and Channel Islands on the site of this geosyncline began in early upper Miocene time, and the upper Miocene diatomaceous shales commonly rest with an angular unconformity upon rocks that are middle Miocene and older. In the Ventura basin, only a few miles to the north, almost continuous deposition of organic shales was progressing during middle Miocene time. A post-Miocene, possibly middle Pliocene, uplift of considerable magnitude supplemented the pre-Pleistocene orogeny of the Santa Monica Mountains, and resulted in folding and faulting of the upper Miocene strata that now occupy the flanks of the mountains.

Along the northern margin of the central Transverse Ranges, from Cuyama Valley southeastward through Lockwood Valley to the northwest side of the San Gabriel Mountains, is a large area covered with continental Miocene conglomerates, sandstones, and siltstones, showing that a land area partly separated the Ventura basin from the San Joaquin basin to the north during late Miocene time. The marine and continental facies have been brought into juxtaposition for several miles by large lateral movements on the San Gabriel fault northwest of Castaic (see Crowell, Contribution No. 6, Chapter IV). Patches of similar nonmarine Miocene strata are present in the San Andreas fault zone along the north flank of the San Gabriel Mountains, and in the Cajon Pass area at least 8,000 feet of upper Miocene conglomeratic sandstone and associated finer-grained rocks is spectacularly exposed (figs. 3, 7). These strata lie unconformably upon lower Miocene marine Vaqueros beds in at least one place in this area. It is interesting to note that the presence of Vaqueros strata in the Cajon Pass area poses a problem in paleogeography and tectonic history, as the nearest other Vaqueros rocks north of the San Andreas fault lie in the San Joaquin Valley, 90 miles to the northwest, and the nearest Vaqueros rocks south of the fault lie in the Santa Ana Mountains, 40 miles to the southwest (Noble, Contribution No. 5, Chapter IV).

A few patches of terrestrial sandstone and conglomerate of doubtful Miocene age occupy fault blocks and slices in the southern part of the San Bernardino Mountains eastward from San Bernardino to points beyond San Gorgonio Pass. The widespread distribution of these and other nonmarine strata to the west and northwest, together with the dominance of plutonic and gneissic rocks as clasts within the strata, indicates that the eastern Transverse Ranges, as well as the granitic Mount Pinos, Liebre Mountains, and Frazier Mountain farther west, were being rapidly eroded during an appreciable part of Miocene time.

Pliocene Rocks. The marine Pliocene section is confined to the central part of the Ventura basin, and extends eastward from points near Goleta to the northwest corner of the San Fernando Valley near Sunland. Between Ventura and Fillmore the generally marine Pliocene soft sandstones, silty clay shales, mudstones, and fine to coarse conglomerates are 13,000 feet to 15,000 feet thick. On Oak Ridge, toward the south rim of the Pliocene basin and a few miles south of this tremendously thick section, 1,000 feet or less of upper Pliocene beds rests unconformably upon organic Miocene shales (fig. 8). In places the marine Pliocene section is not represented at all. In the Goleta-Santa Barbara area, toward the north rim of the basin, from none to possibly 700 feet of largely marine upper Pliocene strata (lower part of the Santa Barbara formation) is preserved, mostly in synclines.

Marine Pliocene clastics of similar lithology attain a thickness of 4,000 feet to 6,500 feet in the deeper parts of the Los Angeles basin beneath the Quaternary cover, but only discontinuous remnants a few thousand feet thick crop out along the northern and eastern margins of the basin northwest of Santa Monica, in the Repetto and Montebello Hills a few miles east of Los Angeles, and at the west end of the Puente and San Jose Hills between Whittier and Pomona.

In both the Ventura and Los Angeles basins the lower half of the Pliocene section contains the most prolific reservoir sands for oil and gas in this region. In the Ventura oil field a maximum of about 7,500 feet of oil-bearing Pliocene strata, excluding repetition by thrust faulting, has been penetrated by wells. This is the thickest known continuously oil-bearing section.

Continental Pliocene sediments, 2,000 feet to nearly 6,000 feet thick, are exposed in the eastern part of the Ventura basin on both sides of the Santa Clara River Valley (fig. 10), and similar beds are preserved on relatively depressed fault blocks in the southwestern part of the San Gabriel Mountains. These deposits are mostly buff gravels and arkosic sands, with interbeds and lenses of reddish and greenish silty clay.

The Ridge basin, north of the Santa Clara River Valley, contains about 29,000 feet of upper Miocene and Pliocene strata, chiefly siltstone, sandstone, conglomerate, and coarse breccia (Crowell, 1950, 1952a, b; Eaton, 1939). The lowermost 2,000 feet of the section is mainly marine, and the remainder represents fluviatile and lacustrine deposition. The enormous thickness of these beds actually is greater than the width of the depositional basin, which was outlined in large part by major faults. The Violin breccia, one formation in the group, is 27,000 feet thick but extends along the strike for a maximum distance of only 4,000 feet. Evidently it accumulated as talus or alluvial debris at the base of the San Gabriel fault scarp, and it grades abruptly into finer-grained strata on the east (Crowell, Ridge Basin Map Sheet, this volume).

The lower part of the Paso Robles formation north of the Santa Ynez River in Santa Barbara County, and the upper part of the continental sands and gravels of the Cuyama and Lockwood Valley area, between the Topatopa Mountains and the San Andreas fault, probably are Pliocene in age. Terrestrial Pliocene strata also are exposed along the northern margin of the San Gabriel Mountains and the southern margin of the San Bernardino and Little San Bernardino Mountains, where in large part they are involved in the San Andreas fault zone. Marine strata of probable Pliocene age (Imperial formation) extend northwestward as a thin tongue into the San Gorgonio Pass area from the Coachella-Imperial Valley. They contain an invertebrate fauna that is markedly different from the faunas in Pliocene strata of the coastal areas (Durham, 1950, pp. 23-33), and thus correlations between the western and eastern parts of the Transverse Range province have been difficult to establish for the marine part of the section.

During middle Pliocene time the Santa Ynez and Topatopa Mountains, as well as Oak Ridge, the Las Posas Hills, and several other low ranges in the Ventura basin, were gently folded up and eroded. Possibly the main uplift of the Santa Monica Mountains—Channel Islands range took place at this time, as well. Marked uplift of the eastern ranges during Pliocene time is attested by the sequence and lithology of the nonmarine sediments that were derived from them.

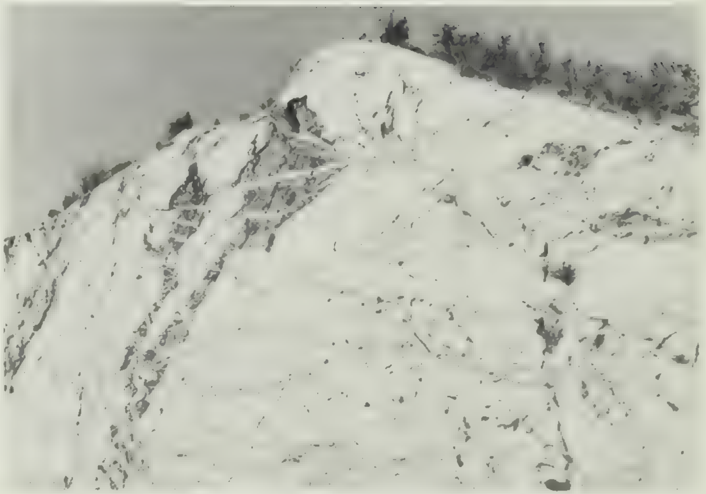


FIGURE 5. Highly sheared anorthosite with dark-colored inclusions of schist quartzite, and amphibolite. These rocks are transected by gently dipping dikes of sheared leuco-monzonite. Soledad Canyon near Ravenna, north side of San Gabriel Mountains.

Pleistocene Rocks. The most remarkable stratigraphic feature of the Transverse Range province is the existence of 4,000 to 5,000 feet of marine Pleistocene strata in the central Ventura basin. These beds have been folded along with the conformably underlying Pliocene section (fig. 1), so that they now show dips of 20 to 75 degrees. They contain both vertebrate and invertebrate fossils of Pleistocene age, and more than 90 percent of the abundant molluscan species among the marine fossils are living today. The basal Pleistocene unit (upper part of Santa Barbara formation) consists mainly of mudstone. It is overlain by an alternation of near-shore soft sands, silts, and gravels. The upper third of the section is mostly nonmarine, the marine basin having been filled by the time these beds were laid down.

At least 2,000 feet of folded lower Pleistocene beds of similar lithology is present in the Los Angeles basin. Resting with strong angular unconformity on the lower Pleistocene San Pedro formation are horizontal to slightly tilted sands, gravels, and silts that contain upper Pleistocene land vertebrates (Rancho La Brea beds and terrace deposits). This great unconformity, which shows angular discordances of 30 to 60 degrees, commonly marks the major Coast Range orogeny during which the Ventura anticline, 3 miles north of Ventura (fig. 1), was folded up far above sea level. In the Los

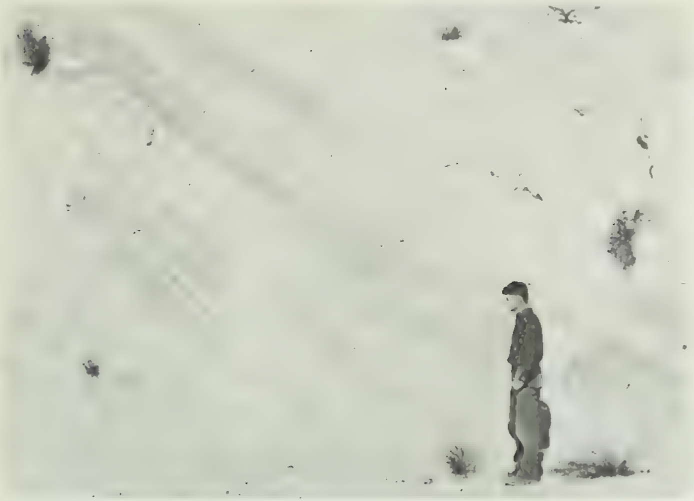


FIGURE 6. Interlayered aplite, pegmatite, and coarse-grained granodiorite. Mill Creek, western San Gabriel Mountains.

Angeles basin several important domal anticlines, on which some of the most prolific oil fields in the State have been developed, were formed or were emphasized at this time.

The effects of this mid-Pleistocene orogeny were widespread, and included intense folding and uplift in all of the older Transverse Ranges, such as the Santa Ynez, Topatopa, San Gabriel, San Bernardino, and Santa Monica Mountains, and in the intra-basin ranges, such as Red Mountain, South Mountain-Oak Ridge, Santa Susana Mountains, San Jose Hills, and Puente Hills. Great thrusts and steep reverse faults, with maximum displacements of 10,000 to more than 15,000 feet, were developed in the Ventura basin and along its margins. These include the Santa Ynez, Big Pine, Simi, Holser, and San Gabriel reverse faults, and the Red Mountain, San Cayetano, Oak Ridge, and Santa Susana thrusts (pl. 4). Faults with steep dips, northeast and northwest strikes, and large components of lateral (strike-slip) movement developed in the Santa Barbara region, and much larger lateral movements occurred along the San Gabriel fault, along the Whittier and Inglewood faults in the Los Angeles basin, and along the San Andreas and associated faults.

STRUCTURE

General Relations. Structurally the Transverse Range province consists of (1) a series of predominantly east-trending, generally steep-sided folds, many of which are broken along their axes or on one or both flanks by compressional faults or thrusts, and (2) large blocks and numerous smaller slices that are bounded mainly by reverse faults or by faults that dip very steeply and have large strike-slip components of movement. Folding either is dominant over faulting or is of equal importance in the basinal areas and in the western ranges that consist predominantly of sedimentary rocks. In contrast, the eastern ranges, in which crystalline basement rocks prevail, are characterized by marginal faults that converge downward beneath the upthrown mountain blocks. The great San Andreas fault, which generally trends northwest along its 640-mile course in California, bends to a more westerly trend in the 180-mile segment that slices obliquely across the Transverse Range province.

Santa Ynez Mountains. The relatively low and broad western part of the Santa Ynez Mountains is a considerably faulted anticlinorium that is bordered on the north by the broad syncline of the lower Santa Ynez Valley. For most of its length farther east, the range is a steeply southward dipping homocline of Cretaceous to Miocene strata that have been tilted up along the Santa Ynez fault zone. This fault generally dips steeply south, and the rocks on its south side have been upthrown from 5,000 to 10,000 feet. It lies near the base of the north side of the range and is bordered on the north for many miles by the synclinorial graben of the upper Santa Ynez Valley.

The Santa Ynez fault commonly occupies the position of the axial plane of a sharp anticline, and hence the crest of the range is on the south limb of this ruptured fold. For a distance of a few miles, the range is a rather open anticline whose north flank is cut by the Santa Ynez fault, which locally dips gently to the south. Between Santa Barbara and Carpinteria, as well as in the vicinity of Ojai, the Eocene and Oligocene strata that form the mountain mass are overturned and dip north at angles as low as 50 degrees. Where the northwest-trending San Rafael Mountains butt against the east-trending Santa Ynez Mountains, the net slip of the Santa Ynez fault has been oblique, the north side apparently having moved downward and westward. Possible transverse arching in the Santa Ynez Mountains may reflect a southward continuation of the San Rafael uplift.

Topatopa Mountains. The eastern Santa Ynez Mountains and their eastern continuation, the Topatopa Mountains, broaden into a complex faulted anticlinorium, and are separated from the higher Pine Mountain-Frazier Mountain ranges on the north by a narrow synclinal graben along upper Sespe Creek. The southern margin of the Topatopa Mountains is generally overturned between the San Cayetano thrust and the axis of a recumbent anticline or group of anticlines that is parallel to the thrust a short distance to the north.

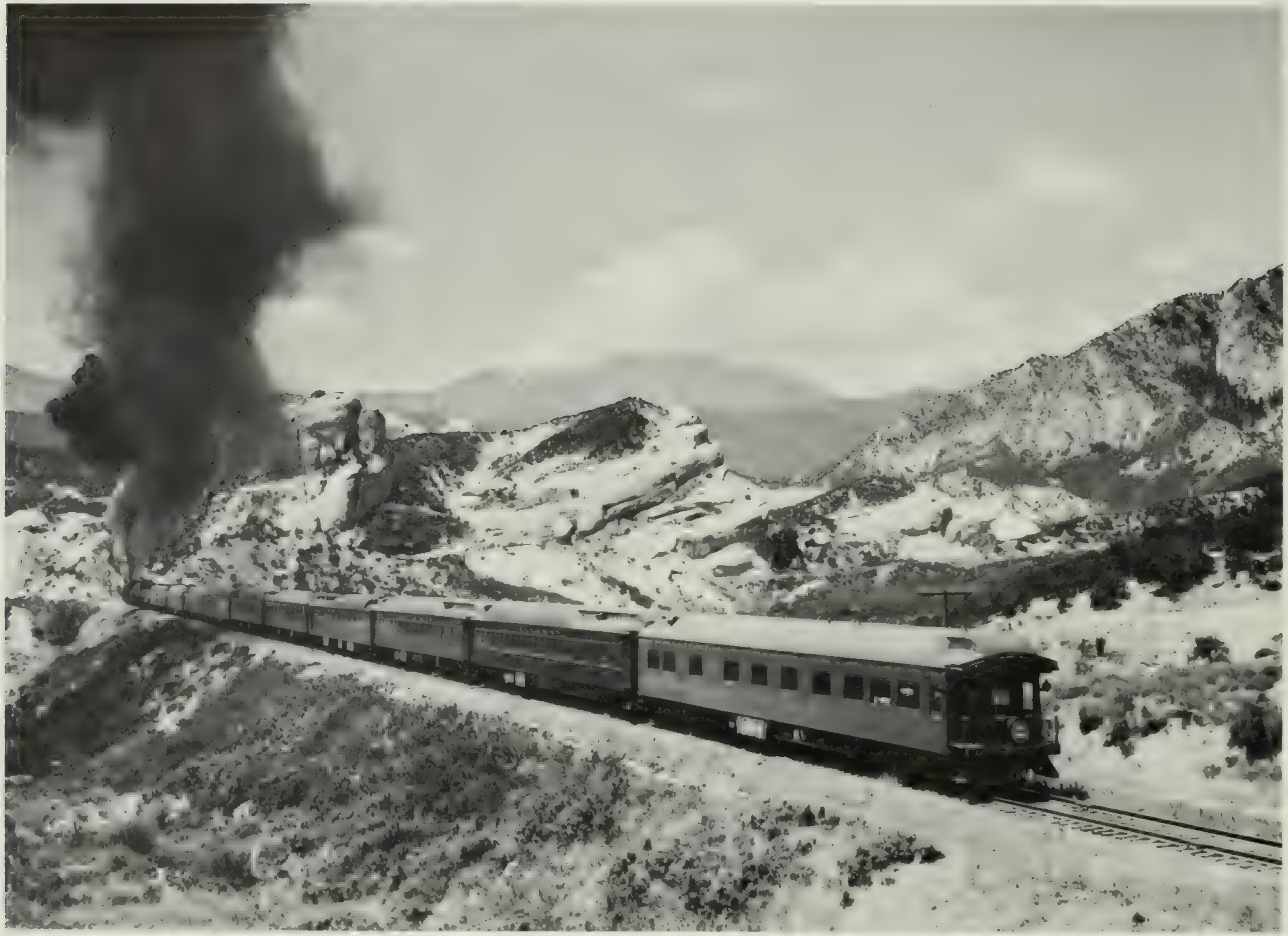


FIGURE 7. Conglomerate, arkosic sandstone, and interbedded finer-grained rocks in the upper drainage of Cajon Creek, between the San Gabriel and San Bernardino Mountains. These nonmarine strata are of late Miocene age. *Photo courtesy of Walter H. Thrall, Jr.*

The thrust extends eastward from the area northeast of Ojai to a point a few miles beyond Piru, and lies along the base of the hills that border the Santa Clara River valley on the north. It dips 15 to 50 degrees northward, and possibly has a maximum dip-slip displacement of 20,000 feet.

As the north side of the Topatopa Mountains is bounded by the generally south-dipping Santa Ynez fault, this range is structurally a flat-topped or gently folded horst with steeply dipping to overturned margins. The Piru Mountains, the eastern continuation of the Topatopa Mountains between lower Sespe Creek and the San Gabriel fault northwest of Castaic, are a gently folded, eastward plunging anticlinorium in Miocene and Pliocene rocks that are closely folded near Hopper Mountain and Piru Creek. The San Cayetano thrust dies out a few miles east of Piru, and from Piru eastward the steeply south-dipping Holser fault is the principal exponent of crustal shortening. This fault is upthrown on the south, with displacements of 2,000 to 5,000 feet, and its sense of movement is opposite to that of the San Cayetano thrust.

The eastern boundary of the Topatopa Mountains is the essentially vertical San Gabriel fault. The north or northeast side of this break is upthrown in the western San Gabriel Mountains, but farther northwest, beyond Castaic, it is downthrown. Several lines of evidence indicate a strike-slip (right lateral) movement of at least several miles along this northwest part of the San Gabriel fault (see Crowell, Contribution No. 6, Chapter IV).

Ventura Basin. The Ventura basin is a highly folded synclinorium that contains a maximum of about 50,000 feet of Tertiary and Quaternary strata, and possibly as much as 8,000 feet of Cretaceous strata. The synclinorium is broken by a number of large thrusts or reverse faults, some of which dip south and others north. Except for its northern margin, the western half of the basin is submerged beneath the Santa Barbara Channel. Most of the larger interior valleys, such as Ojai Valley, Simi Valley, and the Santa Clara River Valley above Saticoy, are synclinal, and the intra-basin ranges of hills or mountains, such as Red Mountain, South Mountain-Oak Ridge, and the Camarillo-Las Posas Hills, are anticlinal. The most extensive lowland area, the Oxnard Plain, is gently folded but considerably faulted beneath its thick alluvial cover.

The central part of the Ventura basin has been subjected to direct north-south compression, resulting in overturning of beds and the development of thrusts or reverse faults on one or both flanks of many of the anticlinal ranges. The Santa Clara and Ojai Valleys are deep fan synclines with both limbs overturned, and the limbs are broken by thrusts that represent movements toward the valleys from both sides (fig. 8). Although Oak Ridge and the Santa Susana Mountains are parts of the same anticlinal uplift, Oak Ridge has been thrust northward along the south-dipping Oak Ridge fault, whereas the Santa Susana Mountains farther east have been thrust southward along the Santa Susana thrust, which dips northward at low angles.

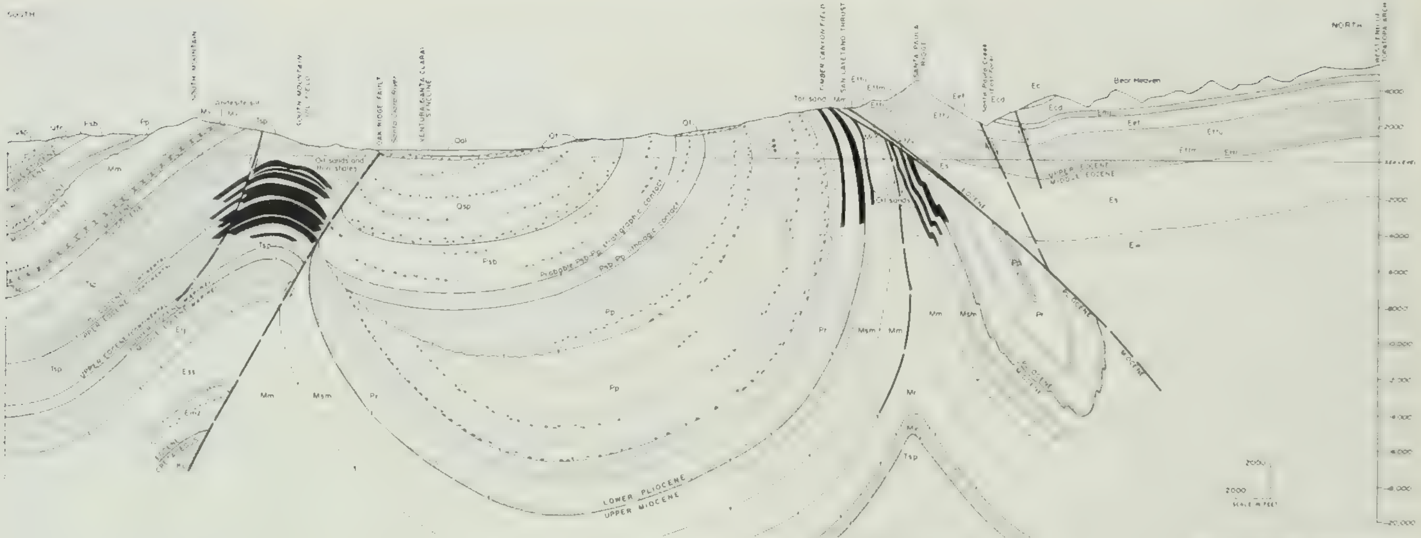
The Ventura Avenue oil field and several other good fields farther west are located on the 16-mile long Ventura anticline, the axis of which lies 3 miles north of Ventura (fig. 1). This anticline has fairly regular limbs that dip at angles of 40 to 50 degrees, but it is severely broken by thrusting, toward both the north and the south, in the subsurface Pliocene beds. These thrusts die out surfaceward into zones of steep dips.

The northwest margin of the Ventura basin includes the southern foothills of the Santa Ynez Mountains and the narrow coastal plain and hills around Santa Barbara, Goleta, and Carpinteria (fig. 9). The foothill belt is a south-dipping homocline that is interrupted by a few anticlines and synclines and is cut by many nearly vertical faults. These intersecting faults trend northeast and northwest, have had oblique-slip movements, and commonly show displacements of a few hundred to a few thousand feet. Santa Barbara and Goleta lie in alluviated valleys that are synclinal grabens, and the Carpinteria alluvial plain is structurally a syncline in Oligocene to lower Pleistocene strata that is cut by faults south of the axis.

The east end of the Ventura basin is a series of closely spaced anticlines and synclines (fig. 10) whose moderately to steeply dipping flanks are broken by the Holser reverse fault. They are cut off diagonally by the San Gabriel fault. Oil fields, surprisingly numerous for such a small area, are present in the vicinity of Piru, Newhall, Castaic, and Saugus. Most of these are on domal anticlines or faulted anticlines, but some represent stratigraphic traps on the flanks or plunging noses of anticlines.

Channel Islands and Santa Monica Mountains. The two largest Channel Islands, Santa Cruz and Santa Rosa, are essentially anticlines that are cut by large east-trending faults along or near their axes. A few smaller faults and folds also are present. The principal faults apparently are oblique-slip features, their north sides having moved downward and westward. The sedimentary and volcanic rocks on San Miguel and Anacapa Islands have generally northeast and north dips. On San Miguel Island they are cut by several nearly vertical faults that strike northwest. The entire Channel Island chain is a faulted anticlinal uplift, and represents the westerly continuation of the Santa Monica Mountains.

The Santa Monica Mountains are essentially a broad anticline that has been extensively intruded by sills, chonoliths, and dikes of diabase and basalt, and has been severely ruptured by steep



This anticline is projected under the thrust from 1 2 mile to the west, where it is exposed in front of the thrust

Geology by Thomas L. Bailey, October 195-

EXPLANATION

Qal, alluvium; Qt, terrace gravels; Qsp, San Pedro formation (clay, sand, gravel); Qfc, Fox Canyon formation (sandstone, conglomerate); Psb, Santa Barbara formation (mudstone); Pp, Pico formation (sandstone, shale, conglomerate); Pr, Repetto formation (sandstone, shale, conglomerate); Msm, Santa Margarita formation (shale, thin sandstone); Mm, Monterey formation (shale, chert, diatomite); Mr, Rincon formation (shale, mudstone); Mv, Vaqueros formation (sandstone, shale); Tsp, Sespe formation (mainly red beds); Ell, Llajas formation (shale, silty sandstone); Ess, Santa Susana formation (shale); Emz, Martinez formation (sandstone, conglomerate, shale); Ec, Coldwater formation (sandstone); Ecd, Cozy Dell formation (black shale, sandstone); Emj, Matilija formation (sandstone, grit); Eef, Echo Falls formation (black shale); Ett, Topatopa formation (Ettu, upper white spotted greenish sandstone; Ettm, middle white grit; Ettl, lower thin-bedded greenish sandstone); Es, Sisar formation (black shale); Ew, Wheeler formation (sandstone); Kc, Chico formation (shale, sandstone)

FIGURE 8. Structure section across a part of the Ventura basin, showing the remarkable thickness of Pliocene strata and the pattern of opposed reverse-fault movements on opposite sides of the Santa Clara River Valley.

oblique faults or cross faults, several of which appear to be tensional in nature. One large strike fault, the Malibu fault, trends approximately parallel to the coast for many miles west from Santa Monica. This is a steeply north-dipping reverse fault with a few thousand feet of displacement. The general plunge of the main anticline of the range is westerly, so that basement rocks are extensively exposed at the east end.

San Fernando Valley. The San Fernando Valley is a faulted synclinorium in Miocene and Pliocene sediments, and is structurally deepest toward the north side of the valley. Its northern margin is ruptured by the Santa Susana thrust zone, which dips northward at low to moderate angles. The north, or hanging-wall block has moved upward and southward 5,000 to 10,000 feet relative to the lower block. On the northwest border of the valley are the Simi Hills, which probably are anticlinal. The inferred anticline is in Cretaceous rocks, and its axial portion is overlapped by south-dipping Miocene strata.

Pine Mountain-Frazier Mountain Area. Pine Mountain is a large anticlinal ridge of Eocene sandstone between the steeply north-dipping Pine Mountain reverse fault on the south and the vertical strike-slip (left lateral) Big Pine fault on the north. Lockwood Valley is a dish-shaped syncline, filled mostly with continental sediments, that lies between the high granitic mountains, Mount Pinos and Frazier Mountain, on the north and east, and the Pine Mountain anticline on the south. The south side of Frazier Mountain is marked by a north-dipping low-angle thrust fault that is a major element in the structurally complex area of junction between the San Andreas and Garlock fault zones. The thrusting was largely Pleistocene

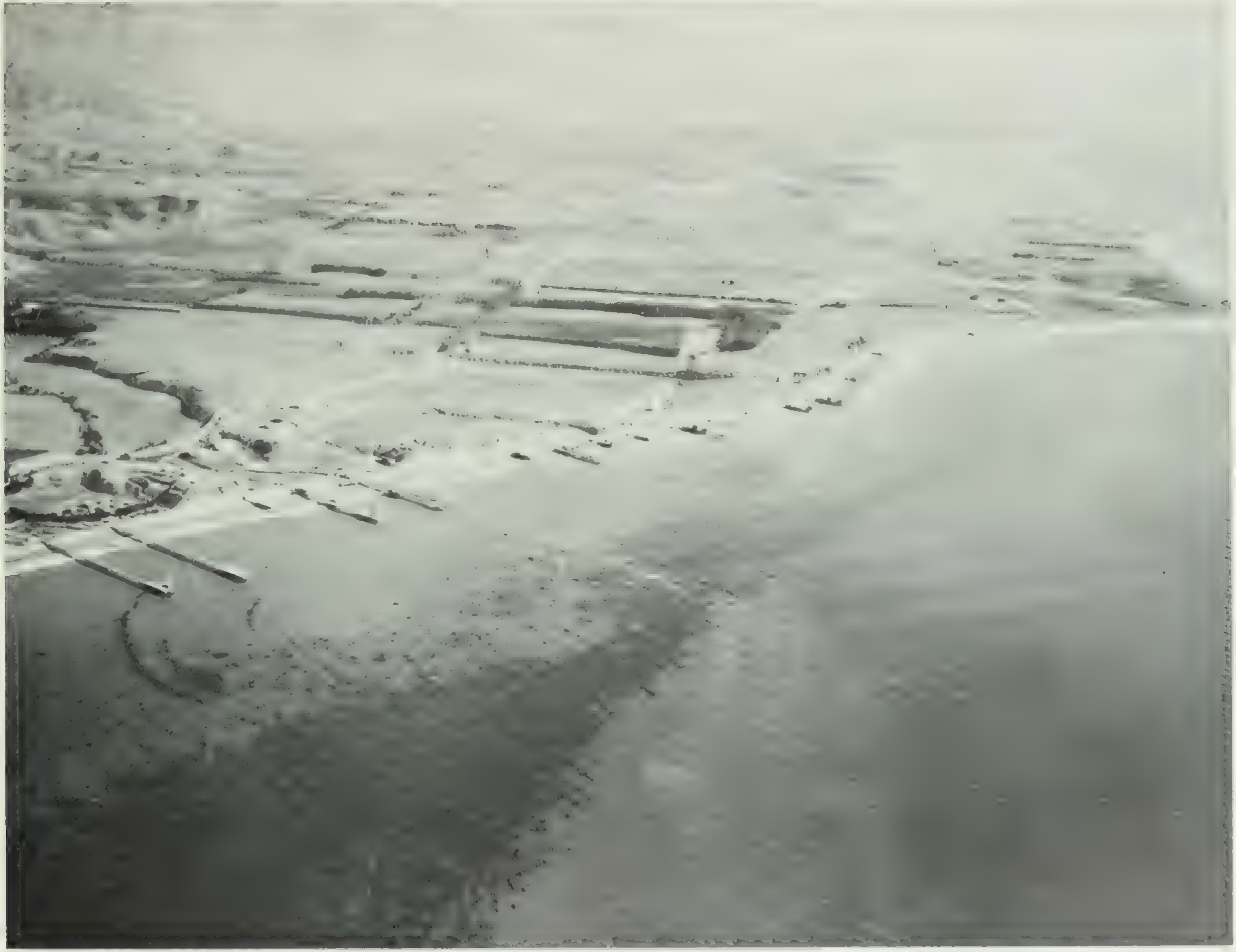


FIGURE 9. The Elwood oil field west of Santa Barbara, showing the narrow coastal plain that flanks the Santa Ynez Mountains. Preferential attachment of kelp to certain beds exposed on the sea floor shows evidence of offshore (westerly) closure of anticline. Goleta Point is at extreme right, and Santa Barbara lies in graben valley in right distance. *Photo by Erickson, 1929.*

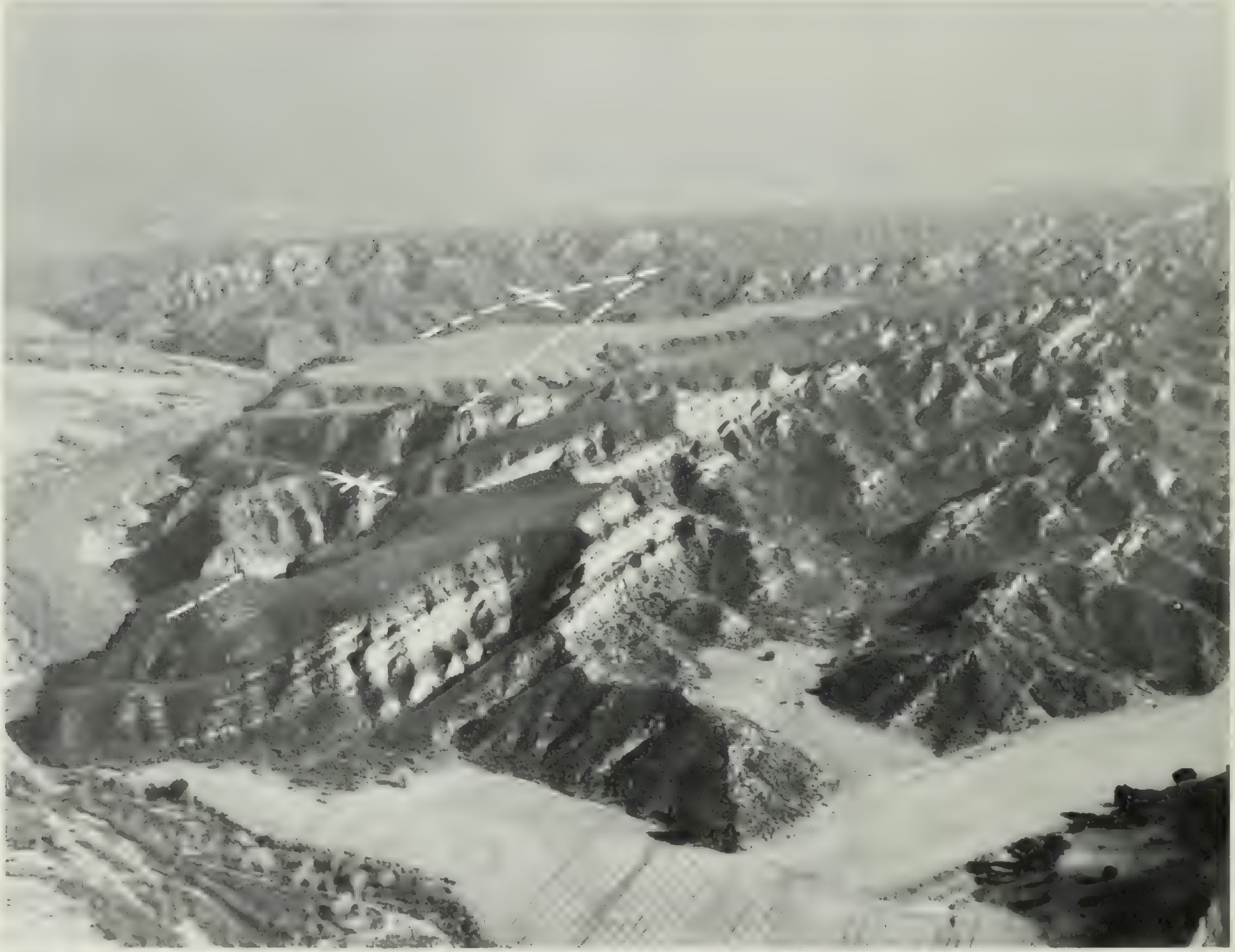


FIGURE 10. Typical exposures of the Saugus formation in the eastern Ventura basin, about 7 miles west of Saugus. These nonmarine strata, of late Pliocene and early Pleistocene age, are here broadly folded. Axial traces of two folds are shown by the dashed lines. *Pacific Air Industries photo.*

in age, and the thrust plane has been sharply folded (Crowell, 1950, p. 1644).

Liebre Mountains and Sierra Pelona. The Liebre Mountains and Sierra Pelona constitute a structurally high mass of crystalline basement rocks into which a narrow wedge of lower Tertiary strata has been dropped between the Clearwater-Bouquet Canyon fault zone and the San Francisquito Canyon fault (pl. 4). These and several other breaks within the ranges are moderately to steeply dipping reverse faults that appear to reflect north-south compression. Some of them have been essentially inactive since early Miocene time, whereas others cut strata as young as Pliocene in adjacent basin areas.

The Sierra Pelona consists almost wholly of Pelona schist that has been folded into a broad anticline whose axis plunges gently west-southwest. The Tertiary strata in the fault-bounded wedge that lies immediately north of the western Sierra Pelona have been much more tightly compressed into numerous folds, several of which are overturned toward the south. The older rocks of the western Liebre Mountains have been thrust southwestward over upper Tertiary strata of the Ridge basin along the Liebre fault zone. Both the Liebre Mountains and the Sierra Pelona are cut off on the northeast by the San Andreas fault zone.

Ridge Basin and Soledad Basin. The Ridge basin is a narrow and very deep structural trough whose filling of upper Tertiary sediments has been compressed into numerous open folds. The axes of most of these folds plunge gently northwest. The lower part of the sedimentary section is cut by faults that die out upward into zones of flexure. These same faults show much larger offsets in the older rocks that appear along the margins of the basin.

Concomitant deposition and deformation in earlier Tertiary time is attested by many of the rocks and structural features of the Soledad basin, which is an open syncline with locally wrinkled flanks and a prevailingly westerly plunge. Strata of probable Oligocene age are faulted against basement rocks (fig. 11), both within the basin and along its margins, but in some places they lie with depositional contact upon these older rocks. Locally the strata have been tightly folded, and in a few areas they form thick homoclines with essentially vertical dip. The Soledad fault, which separates the older part of the basin section from the crystalline rocks of the San Gabriel Mountains to the south (fig. 11), and the Pelona fault, which bounds a part of the basin on the north, are unusual for this region in that their displacement has been chiefly dip-slip and normal, rather than reverse, in nature.

The lower Miocene and younger strata of the basin also have a broadly synclinal structure, but they have been considerably less deformed in detail. They cover many of the earlier faults, including the Soledad and Pelona, but are displaced, generally 500 feet or less, by other faults. They are truncated on the west and southwest by the San Gabriel fault.

San Gabriel Mountains. The San Gabriel Mountains can be regarded as a gigantic horst, lens-like in plan, that is transected by countless fault, shear, and shatter zones. Indeed, no other large mass of crystalline rocks in southern California has been so thoroughly fractured on such a wide variety of scales. Nearly all of the rocks attest to one or more episodes of severe deformation, including mylonitization in several areas, and some of the igneous rocks, like the gabbroic types in the western part of the range, were pervasively deformed during late stages in their crystallization.

The oldest major fault that has been recognized within the range is the Vincent thrust fault, which is marked by a southward and southwestward dipping zone of shear planes and mylonitic rocks whose sinuous trace is plainly exposed on the north side of San Antonio Peak and the high ridges to the west (pl. 4). This break appears to represent northward thrusting of plutonic rocks over the Pelona schist. It cannot be younger than Mesozoic, as it is cut by the youngest intrusive rocks of the late Mesozoic igneous complex (see Noble, Contribution No. 5, Chapter IV).

The younger San Gabriel fault zone traverses the entire range in an essentially east-west direction, and its trace lies 3 to 8 miles north of the mountain front. The steeply dipping and closely spaced breaks in this zone have strongly influenced the pattern of major drainage, and are largely responsible for the linear pattern of the West Fork and East Fork of the San Gabriel River (fig. 12). Movement on them has been dominantly strike-slip in areas northwest of the range, but little is known of the magnitude or direction of their aggregate net slip within the range. The fault zone appears to be offset along cross faults in upper San Antonio Canyon, and its eastern segment butts against the San Jacinto fault zone in the vicinity of Lytle Creek, southeast of San Antonio Peak.

The range is bounded on the north by the Soledad fault, a normal fault that appears to have been relatively inactive during late Tertiary and Quaternary time, and by the San Andreas fault, an essentially vertical strike-slip (right lateral) fault that has remained very active to the present time. The San Jacinto fault, another major break, traverses some of the high country in the northeastern part of the range. It is roughly parallel to the San Andreas fault, and these two master breaks, which are 2 to 4 miles apart in most places,

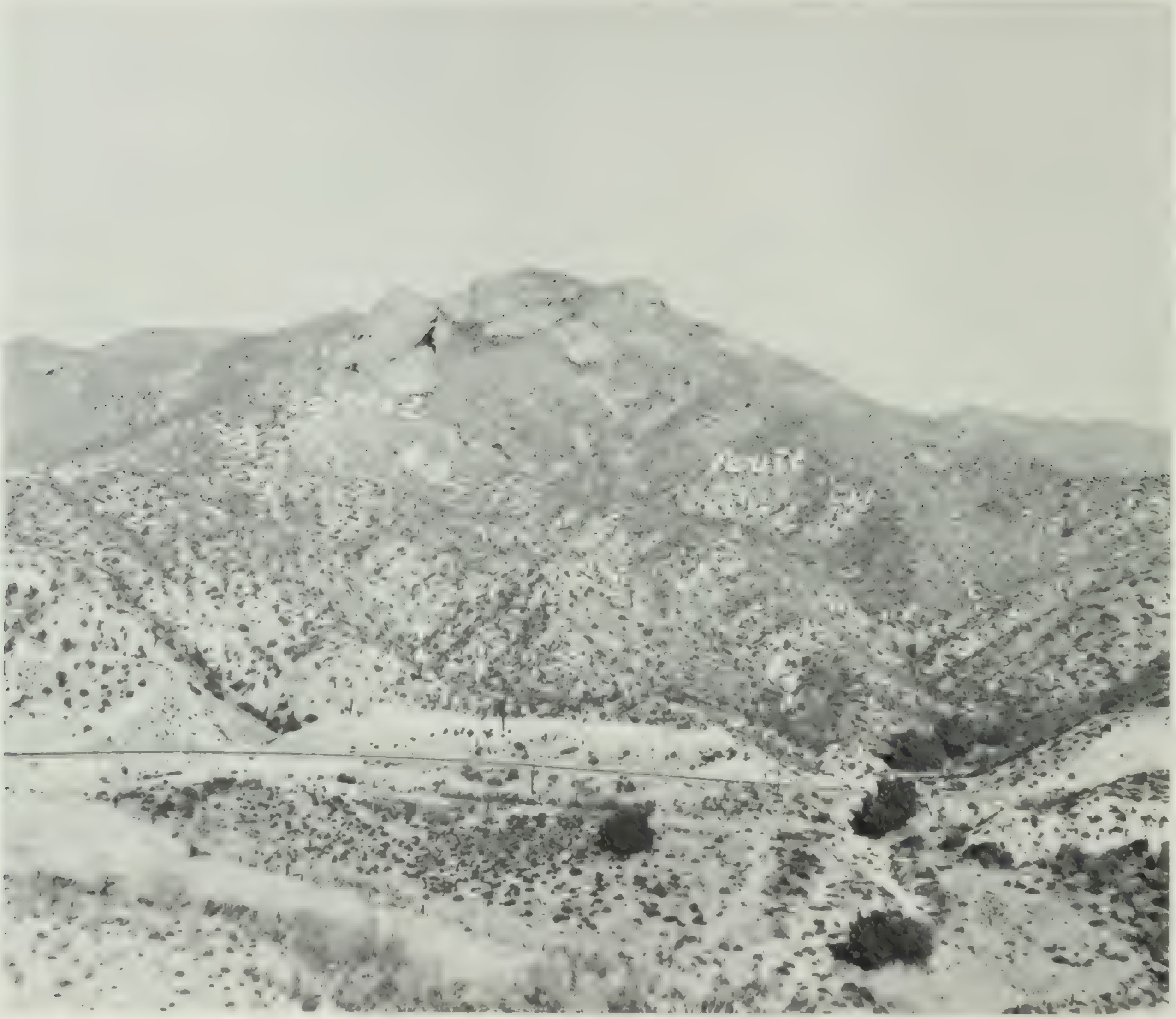


FIGURE 11. Trace of the Soledad fault on the north side of Soledad Canyon. Light-colored anorthosite and associated rocks of the San Gabriel Mountains are in the foreground, and conglomerate and arkosic sandstone of Tertiary age appear beyond the fault in the distance.

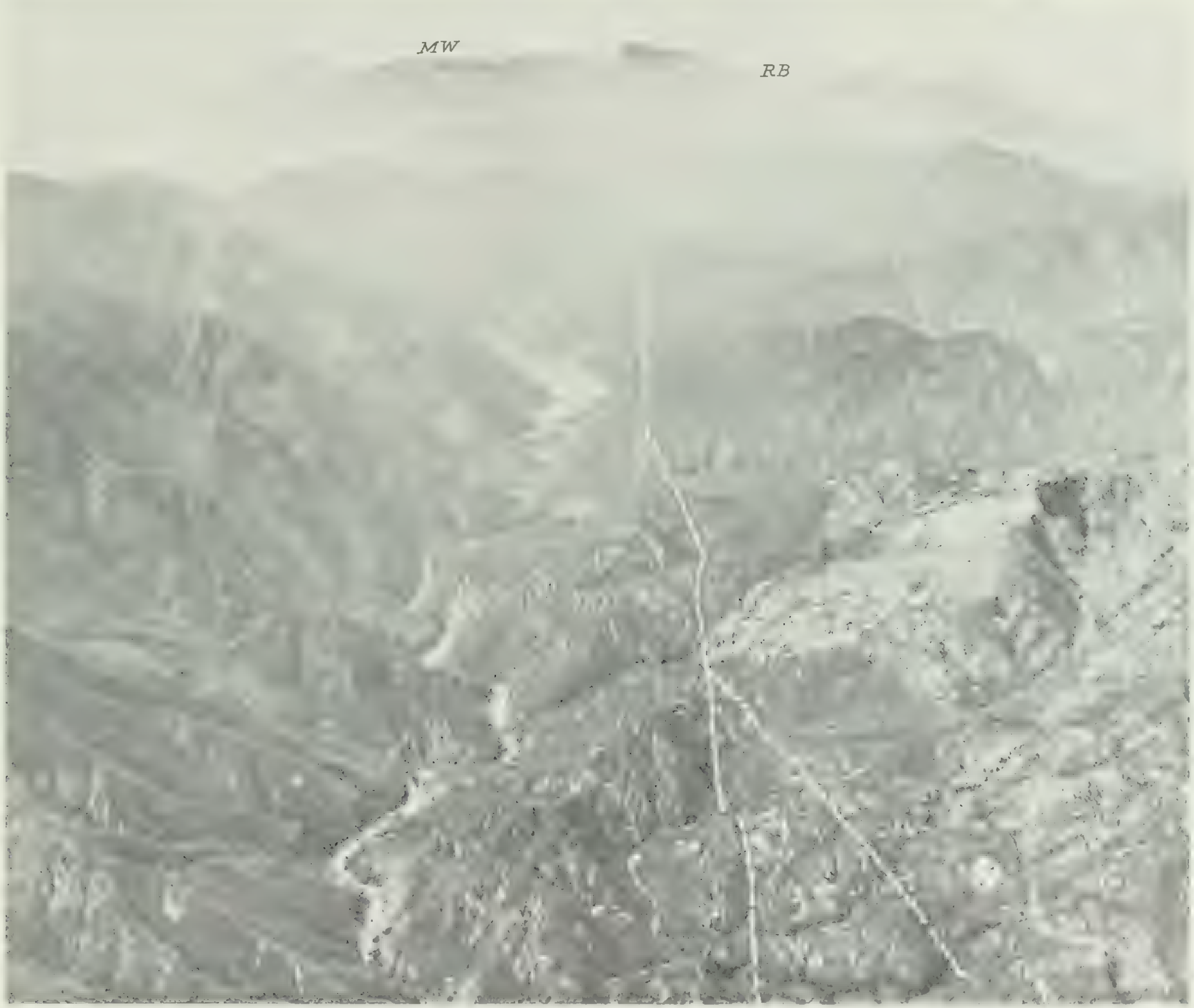


FIGURE 12. Trace of main break of the San Gabriel fault (dashed line) along West Fork of the San Gabriel River; view west toward Mount Wilson (MW) and the Red Box divide (RB). This terrain is typical of the western San Gabriel Mountains. *Photo courtesy Fairchild Aerial Surveys, Inc.*

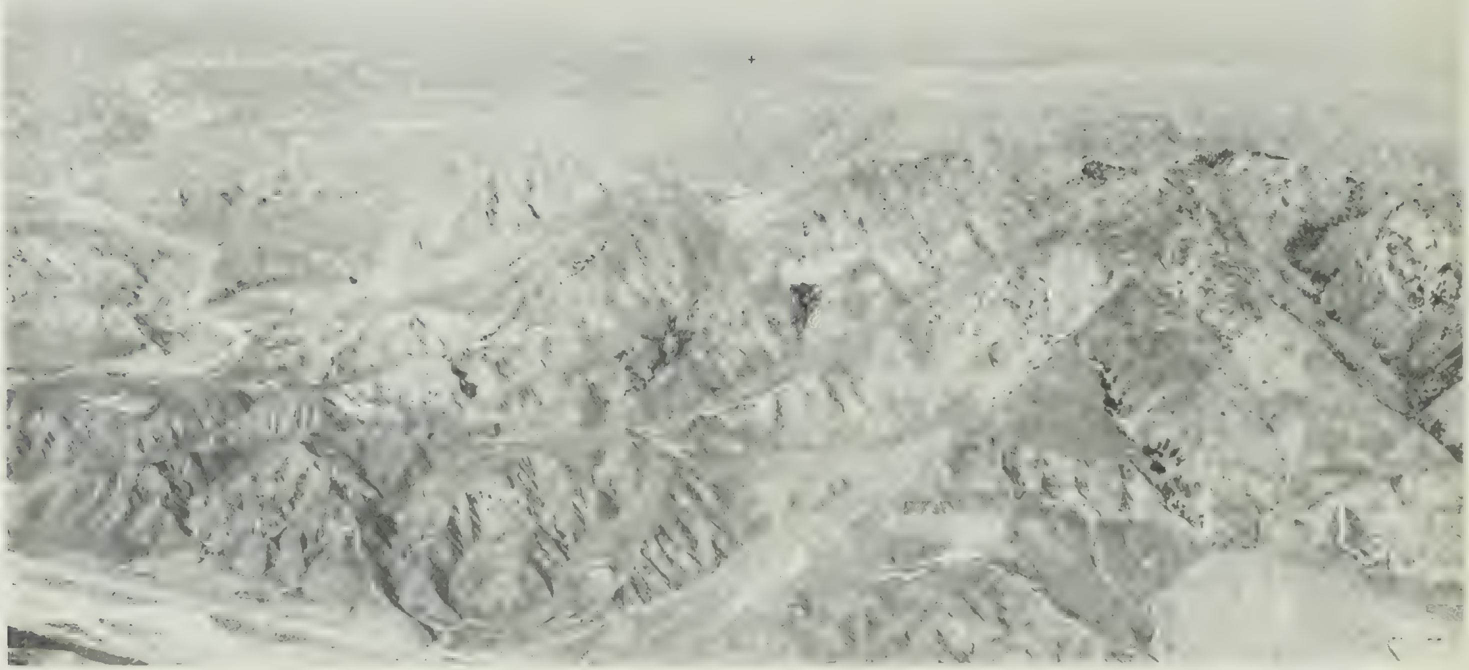


FIGURE 13. The western part of the San Bernardino Mountains; view north into the Mojave Desert region. Cajon Creek is at left, and Cajon Pass is immediately beneath and to left of + mark in center of view. The trace of the San Andreas fault is plainly shown by the aligned saddles, low ridges, and contrasts in vegetation across the foreground. The ridge in foreground at left is mainly Pelona schist, the mountains immediately beyond the San Andreas fault are mainly gneiss and migmatite, and the ridges farther on are Cactus granite. *Photo courtesy Fairchild Aerial Surveys, Inc.*

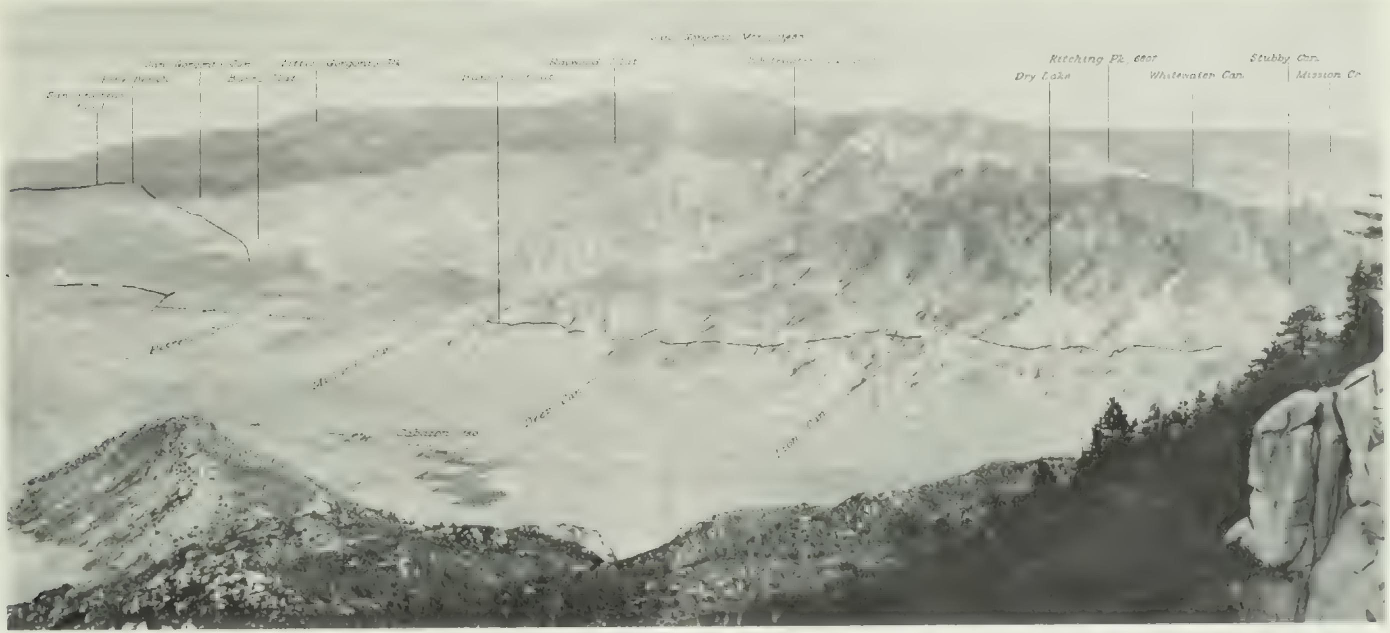


FIGURE 14. The San Bernardino Mountains; view north across San Gorgonio Pass. The traces of the San Andreas and Banning faults, where visible in this view, are shown by black lines. Many other faults are present, but are not delineated. Rocks beyond the Banning fault in center and at right are mainly gneissic types; those between the fault and the floor of the pass are mainly nonmarine strata of late Tertiary and Quaternary age. *Photo and diagramming courtesy of Clarence R. Allen.*

bound an elongate tectonic belt of extreme structural complexity (Noble, Contribution No. 5, Chapter IV).

The south face of the range, which is one of the most impressive scarps in southern California (fig. 2), is defined by the Sierra Madre fault zone, a complex group of branching and en-echelon faults whose prevailing dip is northward beneath the mountains. Individual dips range from steeply south to moderately north, and the dip direction of some of the faults, as traced along their strike, changes back and forth through the vertical. Movement on most of the breaks has been primarily dip slip in nature. The fault zone involves blocks of Miocene sedimentary and volcanic rocks north and east of Azusa, and larger blocks of Miocene and younger rocks farther west, in the area between San Fernando and Big Tujunga Creek (pl. 4).

Transverse upwarping of the range during Quaternary time is suggested by the longitudinal profiles of major elements within the San Andreas-San Jacinto tectonic belt (Noble, 1927, p. 32), and locally by the distribution and attitude of upper Tertiary and Quaternary sedimentary strata that locally veneer both margins of the range. A north-trending axis of broad upwarping may well be marked by the high country that includes Blue Ridge, San Antonio Peak, and Ontario Peak. Similar, though more local and intense, warping of crystalline rocks must have taken place in several other parts of the range, where such rocks lie immediately beneath pronounced folds in Tertiary and Quaternary strata.

San Bernardino Mountains. The San Bernardino Mountains are similar to the San Gabriel Mountains in many structural respects, although their rocks have been considerably less sheared and shattered in detail. The range has been uplifted along the San Andreas and Banning faults on the south (figs. 13, 14) and along several steeply dipping reverse faults on the north. Within the northern part of the range are several thrust faults that dip southward and southwestward at low to moderate angles (Woodford and Harriss, 1928; Guillou, 1953); some of these may be of the same general age as the Vincent thrust fault in the San Gabriel Mountains.

The western part of the range is sliced by numerous subparallel reverse faults that trend west-northwest and dip northward at moderate to very steep angles. Many of them either butt against or merge into the San Andreas fault zone. Patches of Tertiary sedimentary rocks are preserved along several of these breaks. The Arrowhead Springs and Mill Creek faults diverge northward from the San Andreas fault near San Bernardino, and both breaks are marginal to thin slices and much larger and broader blocks of Tertiary and Quaternary strata. The Mill Creek fault traverses the highest part of the range farther east, beyond which area its general trend is continued in the form of the Mission Creek fault, which extends southeastward into Coachella Valley. The two faults almost join in an area that is complicated by the Pinto Mountain fault zone, which extends eastward from the range into the desert region north of the Little San Bernardino Mountains.

The southeastern part of the San Bernardino Mountains is marked by a complex network of faults, particularly in the San Gorgonio Pass area (fig. 14). As pointed out by Allen (see San Gorgonio Pass Map Sheet, this volume), the San Andreas fault in this area is distinguished by several unusual features, among which are absence of typical rift topography along much of its presumed trace, absence of horizontal stream offsets, an abrupt major change in trend of the fault, absence of intense historic earthquake activity associated with the fault zone, and evidence of thrusting rather than strike-slip movements during Quaternary time. The relationships among the faults in the pass area are extremely complicated, particularly in terms of their respective periods of movement, and reconciling the unusual features of this zone with those of the San Andreas fault zone farther northwest constitutes one of the most provocative structural problems in southern California.

ECONOMIC FEATURES

The major current economic assets of the Transverse Range province are assuredly liquid. Impressive accumulations of petroleum have been found in many of the western ranges and basin areas, and the long-continued search for additional reserves has contributed much to the present understanding of stratigraphic and structural complexities in these areas. Many of the occurrences of oil and gas have been noted in previous paragraphs, and more detailed discussions appear in Chapter IX of this volume.

Perhaps even more important to the economy of southern California are the water resources of the province. In particular, the concentrations of ground-water in certain strata (mainly Pleistocene) of the Ventura basin and basins that lie adjacent to the San Gabriel and San Bernardino Mountains have played a vital part in the development of the region. Doubtless these resources will continue to be important in the future, even though they are far from adequate in terms of demands in the more densely populated and industrialized areas. Some of the specific problems and features of water occurrence are discussed in Chapter VI of this volume, and the occurrence of mineral deposits is discussed in Chapter VIII.

Among the nonmetallic mineral resources of the Transverse Range province, sand, gravel, diatomite, and gypsum have been most important commercially. More than half of the sand and gravel produced in the State has been obtained in this province from alluvial deposits of Quaternary age, especially along the southern margin of the San Gabriel Mountains. Placer gold has been recovered as a byproduct from deposits near Azusa. At Ventura lower Pleistocene mudstones are quarried, crushed, and fused in furnaces to form glass-like pellets that are widely used as a light-weight aggregate. Diatomite of moderate to high grade is widely distributed in Miocene and Pliocene marine strata in the western half of the province, particularly in the Santa Ynez Mountains, Purisima Hills, and Santa Rita Hills. It is most abundant in the lower part of the Sisquoc formation (Dibblee, 1950, pp. 75-79), and the largest known commercial deposit of diatomite in the world constitutes about 1,000 feet of this formation in the northern foothills of the Santa Ynez Mountains near Lompoc.

Bedded gypsum has been mined from a nonmarine section of Miocene age in the upper Cuyama River basin of northwestern Ventura County, and gypsite has been obtained from the outcrops of these strata. Gypsite also has been mined from the outcrops of Oligocene (?) gypsiferous siltstones in the eastern part of the Soledad basin. Colemanite and other borate minerals were mined years ago from Oligocene (?) lake beds in the Soledad basin, and from similar beds in the Lockwood Valley area of northeastern Ventura County.

Concentrations of graphite occur in the metamorphic rocks of the Sierra Pelona, the Verdugo Hills, and the San Gabriel Mountains (Beverly, 1934), and numerous small deposits have been mined or prospected. Stone for flagging and other decorative uses has been quarried from certain parts of the Pelona schist. Some of the other pre-Cretaceous terranes contain large reserves of limestone, especially in the San Bernardino Mountains, and both limestone and gypsum are present in some of the desert ranges to the east. A little feldspar and mica has been obtained from pegmatite deposits in the San Gabriel Mountains, San Bernardino Mountains, and the Frazier Mountain area.

Among the metals, large quantities of magnetite and hematite are being mined from extensive contact-metamorphic deposits in the Eagle Mountains, whence they are shipped to blast furnaces at Fontana, west of San Bernardino. The ore was formed by replacement of calcareous strata of Paleozoic or earlier age (Harder, 1912; Hadley, 1948). Large deposits of ilmenite and titaniferous magnetite are present in the western San Gabriel Mountains, where they are associated with anorthosite and other gabbroic rocks (Moorhouse, 1938; Oakeshott, 1948). These minerals also are concentrated in numerous Recent stream deposits, and several small placer accumulations have been worked commercially. Gold-bearing veins and placer deposits have been mined, generally on a small scale, at many localities in the San Gabriel, San Bernardino, and Little San Bernardino Mountains, as well as in parts of the basins and western ranges where basement rocks are exposed. The combined production from these operations has been surprisingly large.

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7. GENERAL GEOLOGY OF THE OFFSHORE AREA, SOUTHERN CALIFORNIA*

BY KENNETH O. EMERY †

Introduction. The submarine area of about 31,000 square miles that is bounded by the southern California shoreline, the continental slope, and the 31° 30′ parallel of latitude is among the best known sea-floor areas of comparable size in the world. However, even here the unknown geology far exceeds the known. Because of the relative inaccessibility of the submarine area, each new fact gained is expensive in terms of both time and effort, and thus it receives more attention and interpretation than an equivalent new fact of land geology. Care constantly must be exerted to avoid over-exploitation of the facts, and this can be done mainly by judging what is reasonable in terms of knowledge borrowed from the geology of the adjacent land. In turn, the field of submarine geology repays its debt by furnishing actual measurements of the environments in which sediments are being deposited, for use in estimating the environments of formations of sedimentary rocks now on land.

Submarine geology can be divided conveniently into three basic fields: physiography, lithology, and sedimentology, in each of which special tools and techniques have been developed. From data of these fields interpretations of structure and geological history can be made.

Physiography. In general, the region consists of many blocks of roughly equal size that bear a close resemblance to the fault blocks of the Basin Range province in Nevada and eastern California (figs. 1, 3). The slopes that bound the blocks are fairly straight and steep (5° to 10° average and more than 40° locally), and some terminate downward in linear depressions similar to sag ponds. Earthquake epicenters are more frequent on the basin side of these slopes, suggesting that the slopes reflect the presence of normal faults that separate horsts and grabens. For convenience the blocks will be referred to as horsts and grabens though later work may show that some of them are due to folding rather than to simple block faulting.

Many of the horsts rise to relatively shallow depths beneath the ocean surface as banks or even rise above sea level as islands. Flat shelves, a quarter of a mile to 15 miles wide, fringe the margins of the islands and of the mainland. These are the island shelves and the true continental shelves. Their seaward edges generally are 150 feet to 450 feet deep. The tops of shallower banks also are flat, or are marked by small erosional remnants that rise above the general level. Similar shelves now above sea level on islands and mainland are recognized as elevated wave-cut terraces.

Transverse to the shelves are submarine valleys and canyons that partially or entirely cross the shelves and continue down the adjoining slopes. These features are present along the mainland, off several of the islands, and even at the side of at least one bank. Though much has been written about them, little really is known of their origin.

Between the horsts are grabens that form 13 or 14 distinct closed basins and one trough. The bottoms of several of the basins are as much as 6,000 feet below the tops of the adjacent horsts. These vertical differences may have been even greater before erosion lowered the horsts and sediments partially filled the basins. At intermediate depths are sills, or lowest points of the rims around the basins. The sills of three basins lie more than 2,000 feet above their floors. Curiously, each of four basins has two sills whose depths are within 200 feet of each other, and another basin even has five sills within a vertical range of about 120 feet. No specific mechanism is known to be responsible for this similarity of sill depths, yet mere coincidence seems implausible. A large body of water trapped below the sill level in each basin exerts a strong influence on the character of the sediment that is being deposited.

Lithology. The surface geology of the horsts is quite different from that of the grabens. The horsts consist of rocks partially covered by a thin layer of coarse-grained sediments, whereas the grabens consist dominantly of finer-grained sediments. Rocks of the topographic highs range from Jurassic (or possibly pre-Jurassic) to Plio-Pleistocene in age, as shown in figure 1. The most common basement rock is Franciscan-like schist that occurs on several of the islands and banks; granitic basement rocks are known only on Santa Cruz Island. The distribution of basement rock types thus closely corresponds to that of Reed and Hollister's (1936) metamorphic Southern Franciscan and granitic Anacapia Provinces.

Cretaceous sandstone and shale have been found only in a small area near the shore at San Diego. Eocene shales occur in the same area, and also on and around San Nicolas, Santa Cruz, Santa Rosa, and San Miguel Islands. Oligocene rocks have not been recognized in the offshore area. Miocene rocks have by far the widest distribution in the region and have been reported from all the islands and from most of the sea-floor rock samples. The most common types are shales and cherts with some limestones. Volcanic rocks, mostly andesite, are exposed at the surface on nearly all islands, and, as these are of Miocene age, it is presumed that similar rocks from the sea floor are of the same age.

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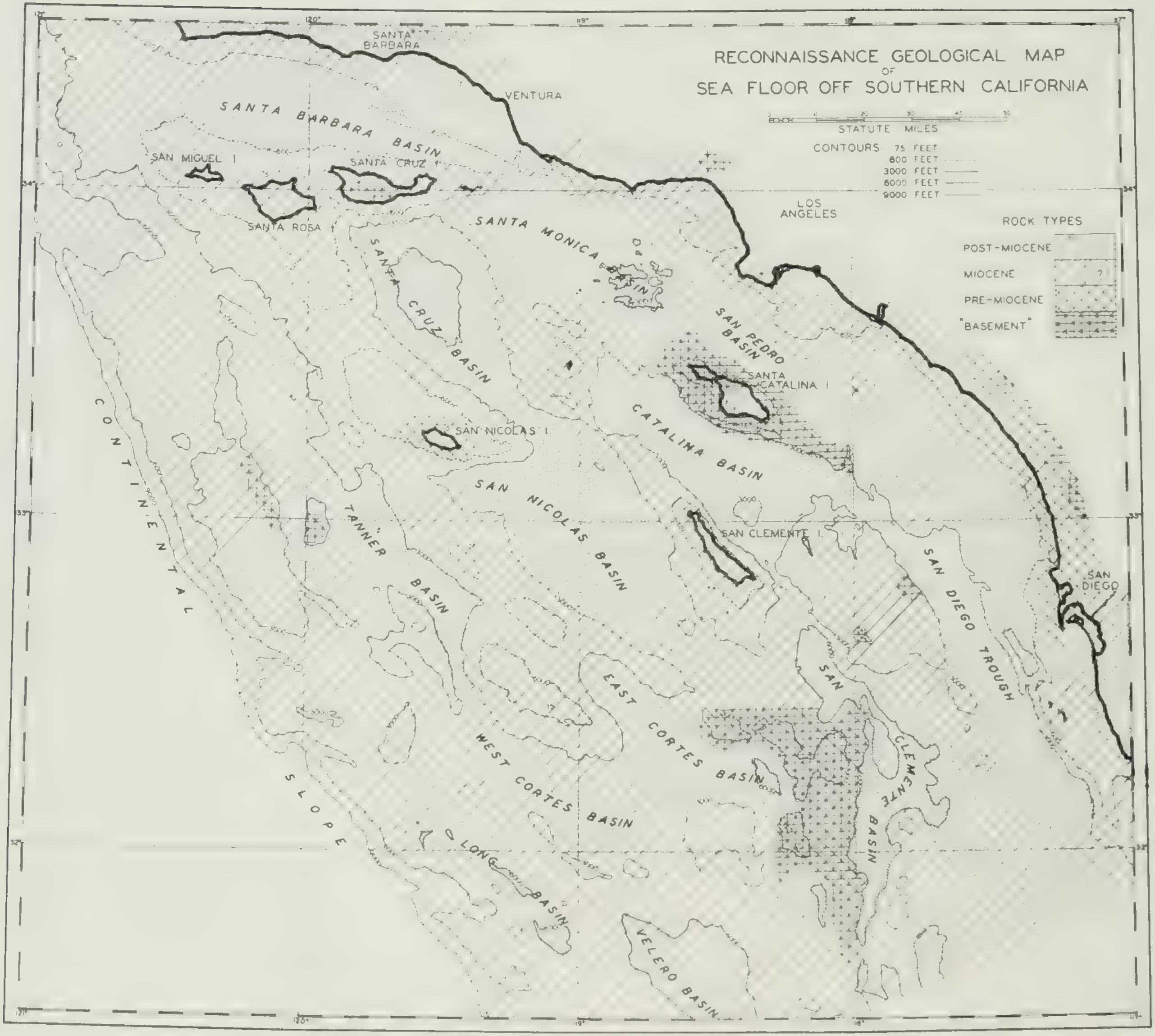

FIGURE 1. Geologic map of sea floor and adjacent land, southern California.

Among the more interesting rocks is phosphorite, which occurs as nodules as much as 2 feet in diameter. Much of the phosphorite contains middle and late Miocene Foraminifera, and other phosphorite contains Plio-Pleistocene forms. It also encloses glauconite grains and manganese-oxide films that generally characterize unconformities. The heavy-mineral content of the phosphorite is similar to that of the residual component of the surrounding loose sediments. The phosphorite thus is believed to have formed on the present banktops in a non-clastic environment. Its presence indicates a middle or late Miocene date for initiation of the block-type sea floor topography. This indication is strengthened by the general absence of clastic Plio-Pleistocene rocks on the bank tops. Locally, however, Plio-Pleistocene mudstones have been found on the slopes, and in one area, off San Diego, they form the top portion of a bank. This suggests that deformation may have been recurrent, or possibly may have taken place at different times in various parts of the region.

The truncation of Jurassic, Cretaceous, Eocene, and Miocene rocks by the mainland and island shelves indicates that these shelves are erosional, not depositional, features. Plio-Pleistocene mudstone is present locally on the shelves, where no similar sediment accumulates today, and hence shelves must have been cut in post-Pliocene times, probably during one or more of the Pleistocene stages of glacially lowered sea level.

Sedimentology. The shelves, banks, slopes, and basins are distinctly different environments of deposition, and they have characteristically different types of sediments. The shelves are closest to the source of sediments, the land, but they do not have the greatest thickness of sediments because of the recency of their formation and because their shallowness results in by-passing of the finer grain-sizes of material. The thin blanket of coarse sediment that partly covers the rocks of the shelves consists of five components: residual sands and gravels derived from underlying rocks; relict sands and gravels that represent past times of lowered sea level (such as submerged beaches); organic sands from shells and foraminiferal tests; authigenic sands and gravels of glauconite and phosphorite; and clastic gravels, sands, and silts contributed by streams and also derived from shore erosion. The clastic sediments probably are dominant. Taken alone, they grade from coarse nearshore to fine offshore. On the mainland shelf, the organic and authigenic sediments are subordinate, but on island shelves they may be dominant.

Sediments of the bank tops consist of the same five components, but the organic and authigenic components are dominant. Present-day clastic sediments are absent or minor in quantity because such sediments, in moving from shore, are trapped in the basins before they can reach the banks.

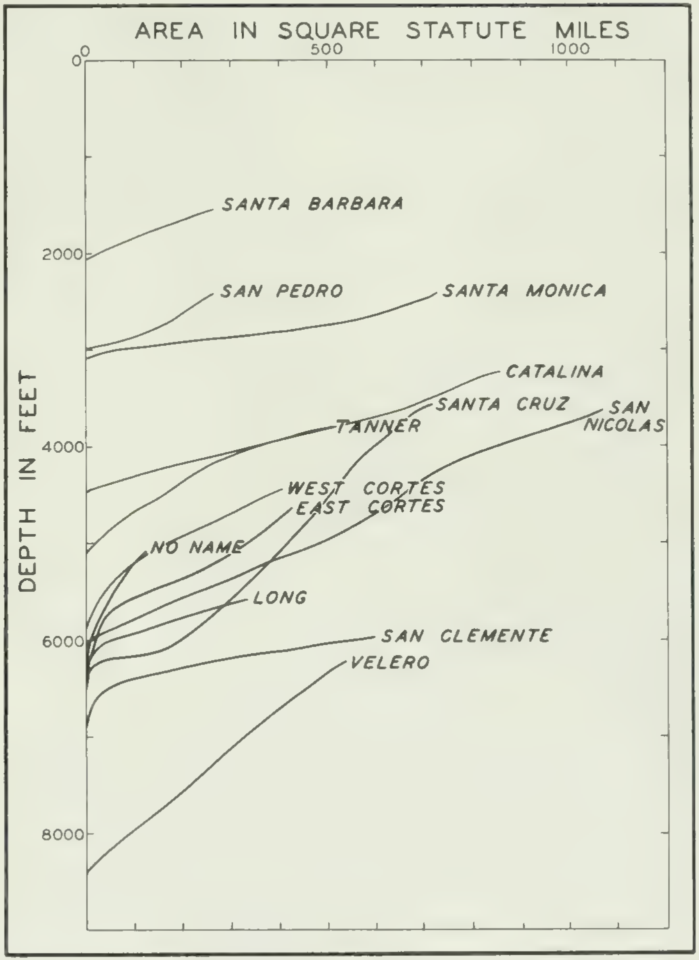

FIGURE 2. Hypsographic curves for basins. The slopes are gentler for the shallower (nearer shore) basins, and the deeper basins generally lack flat floors.

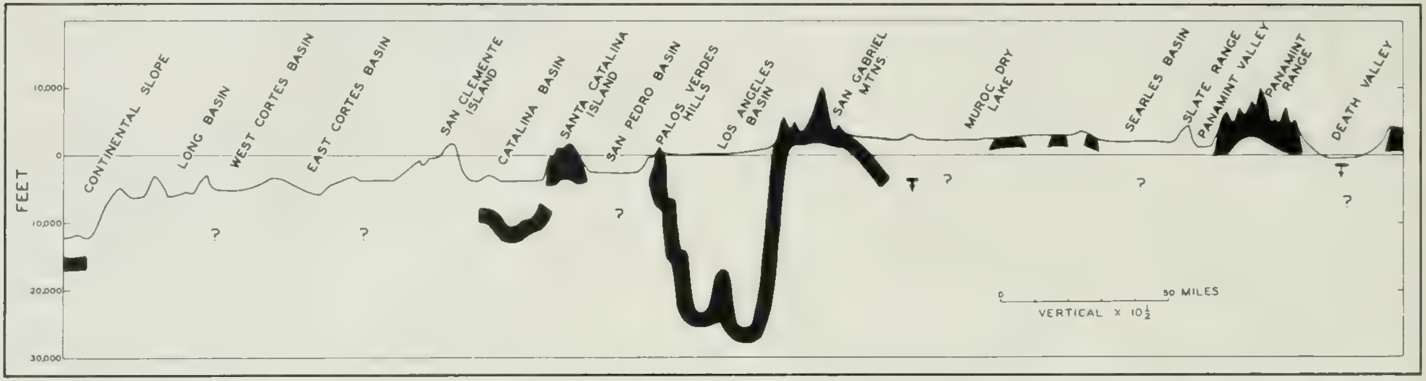

FIGURE 3. Profiles of sea-floor and land topography from the continental slope through the Los Angeles basin to Death Valley. The heavy black line indicates the topography of the basement rocks, as compiled from various sources.

Like the shelves and bank tops, the slopes appear to have only a thin layer of sediments, but for a different reason. The slopes are many times steeper than the depositional foreset beds of large deltas, and, as a result, one might expect that slides periodically should carry any accumulations of sediment down to the adjoining basin floor. In any event, experience has shown that rock commonly forms, or closely underlies, the surface of the slopes.

The basins and troughs, or grabens, are the sites of deposition of the bulk of the present sediment. In general, the basins closest to shore have the shallowest, broadest, and flattest bottoms (fig. 2) and contain the coarsest detrital sediment, suggesting that the sediments are thicker than in basins farther offshore. In addition, several of the nearshore basins are almost filled to their sills, and one is completely filled as a submarine trough; the similar Los Angeles and Ventura basins have been filled to levels above that of the ocean. These latter basins contain more than 10,000 feet of Plio-Pleistocene and Recent sediments, and the total thickness of all rocks above the basement probably exceeds 25,000 feet, although data are not very complete. Incomplete data from wells and seismic studies also indicate that great thicknesses of sediment are present in other land basins farther north. According to seismic measurements several of the offshore basins contain 7,000 to 9,000 feet of sediments and rock above their floors of crystalline rocks.

The organic components of the basin sediments are of especial interest because each of the basins can be considered representative of a stage in the filling of the Los Angeles basin, in which so much organic matter has been converted to oil that this one basin has yielded about ten percent of the total past oil production of the United States. In general, the percentage of calcium carbonate, consisting chiefly of pelagic foraminiferal tests, increases with distance from the mainland shore, whereas the content of organic matter composed of various hydrocarbons is low both in the nearshore and the far offshore basins, and is highest in basins at intermediate distance from shore.

The rapid deposition of clastic sediment near the shore results in dilution or masking of both calcium carbonate and organic matter. Far offshore, where clastic materials are deposited only slowly, calcium carbonate is less diluted and may compose the bulk of the sediment, forming *Globigerina* ooze in the deep sea area. The same slow rate of deposition of clastic sediments results in prolonged exposure of organic matter to oxygen-bearing waters, thus causing it to be oxidized and lost from the sediment. At some intermediate distance from shore, clastic sediments are deposited slowly enough to not mask the organic matter, and yet rapidly enough to bury much of the organic matter before it is destroyed by oxidation. In this region the optimum distance from shore is about 50 miles, at which distance the basin sediments contain about 10 percent of organic matter.

General Interpretations. Figure 1 shows that the islands are concentrated in the northern half of the submarine area, and that most of the deep basins are located in the southern half. A more complete analysis is presented in figure 4, in which the height above sea level or the depth below sea level of the top of each major horst or mountain is plotted against distance south of the northern border of figure 1, latitude 34° 30′. The same procedure was followed for the

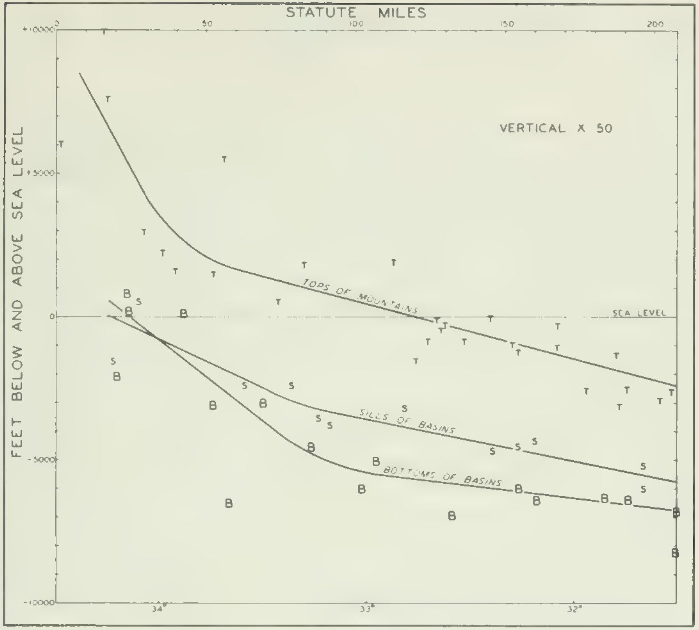

FIGURE 4. Plot of the variations of the height or depth of mountain tops (T), basin floors (B), and basin sills (S) with distance south of latitude 34°30′, the northern border of figure 1. Data are restricted to the area shown in figure 1.

bottoms of the basins and for their sills. It is evident that all three features systematically decrease in altitude toward the south. The steep part of the curve for the tops of mountains results from the presence of the high Transverse Ranges at the north, and the steep portion of the curve for the bottoms of basins is, at least in part, the result of the rapid decrease in rate of deposition of basin sediments in an offshore direction.

On land, the sills are lower than the basin floors because these basins are filled to overflowing. Far to the south the sills are not as high above the basin floors as at intermediate distances, possibly because the original basin-forming deformation was less intense there. Aside from the local steepening, all three curves show an average southward decrease in altitude of about 3,000 feet per hundred miles, or a slope of about one-third degree. Three hundred miles southeast of the southern border of figure 1, the sea floor again rises to form the spur of Baja California. Evidently the submerged margin of the continent between this spur and Point Conception has undergone a broad downwarp. The deformation must have occurred in pre-Pleistocene times, because the depth of the continental shelf varies only a few hundred feet in this distance. Whether the downwarp occurred before or after the smaller-scale block faulting is not yet known.

A comparison of the surface topography and the basement topography of the land and sea floor is shown by the profiles of figure 3. Though no claim to great accuracy in the basement topography can be made, it is evident that both regions are roughly similar, and that the high areas contain outcrops of older rocks and the low areas contain a thick fill of sediment above these older rocks.

It is perhaps not unreasonable to suggest that the topography was largely developed in pre-Pliocene times in both the sea floor and the western part of the Basin-Range province on land. These two areas are separated by the Transverse Ranges (San Gabriel Mountains and others), which are high, have steep slopes, and receive the greatest rainfall of the region. Rapid erosion of the Transverse Ranges should have resulted in rapid deposition of sediments in both the sea-floor basins and the land basins that flank these ranges. This would have led to filling of the Los Angeles and Ventura basins, which formerly were of the sea-floor type. In the western part of the Mojave Desert, former basins of the Basin-Range province also have been filled to overflowing, but with continental sediments. A smaller quantity of sediments has reached the sea-floor areas farther to the south, as well as land areas to the northeast, so that present closed (unfilled) basins occur at great distances both north and south of the Transverse Ranges.

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8. GEOLOGICAL SUMMARY OF THE SAN JOAQUIN VALLEY, CALIFORNIA

By Harold W. Hoots,[*] Ted L. Bear,[*] and William D. Kleinpell [†]

INTRODUCTION

The San Joaquin Valley lies between the California Coast Ranges and the Sierra Nevada, and extends northwestward from the San Emigdio and Tehachapi Mountains to the vicinity of Stockton. It is 250 miles long and 50 to 60 miles wide (fig. 1). Its almost featureless alluvial floor, interrupted here and there by low hills that reflect local anticlines, conceals the axis and much of the flanks of the San Joaquin basin, one of the major structural features of California.

Outcrops of Tertiary formations along the borders of this extensive valley contain seepages of oil that attracted the attention of early prospectors and led to the discovery of three major oilfields, McKittrick (1887), Coalinga (1887 and 1901), and Kern River (1899). The San Joaquin Valley has since become, and will long continue to be, one of the most important oil-producing districts of California. Its geology has been studied and restudied by several generations of geologists, and is perhaps as well known as that of any major oil producing district; it still holds a particular appeal to petroleum geologists because of the certainty that there lies hidden within the intricate structure and the remarkably varied stratigraphy of this basin a sizeable number of commercial oilfields that some day will be found.

Many of the oilfields of the San Joaquin Valley, from the Coalinga and Helm fields on the north to the Midway-Sunset, Kern River, Edison, and Tejon Ranch fields on the south, produce from stratigraphic traps that exist by reason of unconformities, or by reason of lateral changes in the lithology of the petroliferous rock section. These unconformities and/or lateral changes in lithology are distributed throughout a thick Tertiary section, and locally extend downward to involve older rocks, either Cretaceous or basement schist, that immediately underlie the Tertiary section. Because these numerous stratigraphic traps resulted in large part from tectonic events that affected the distribution and character of Tertiary land areas, seas, and sediments, the authors have devoted much of this paper to brief discussions of paleogeography and the evolution of structure.

STRATIGRAPHY

Upper Cretaceous and Cenozoic rocks of the San Joaquin Valley form a stratigraphic section of unusual thickness and remarkably varied lithology. The following table classifies these rocks broadly as to age, and includes general information as to lithology, maximum thicknesses, and known importance for oil and gas. Names and relations of stratigraphic units are shown in figure 2.

General description of rock section.

Age	Lithology	Maximum thickness (feet)	Established importance for oil and gas
Quaternary	Clay, sand, and conglomerate; buff to gray and greenish gray color, poorly cemented and poorly sorted. Almost entirely alluvial-fan and lacustrine material.	8,000—10,000	Small in few localities.
Pliocene	Soft greenish-gray claystone and interbedded permeable sands; upper third non-marine and marine; lower two-thirds marine, particularly in central basin areas. Megafossil control.	8,000—9,000	Large and extensive, mostly along borders of southern part of valley. Ultimate recovery, 48 percent of estimated proved oil.
Miocene	Brown and gray clay-shale and hard siliceous shale, with numerous permeable sandstone and conglomeratic sandstone members; marine with *Foraminifera*, diatoms, and megafossils, except uppermost and basal non-marine members along eastern and southeastern borders. Basaltic and andesitic flows and intrusions in lower part along southeastern border.	12,000—13,000	Large and extensive throughout valley. Ultimate recovery, 44 percent of estimated proved oil.
"Oligocene" and upper Eocene	Gray and brown shale and hard siliceous shale with some thin and thick permeable sands in local border areas; marine with *Foraminifera* and megafossils, except for red and green non-marine beds in "Oligocene" of eastern and southeastern borders.	8,000—9,000	Large in several fields along western and southern borders of valley. Ultimate recovery, 8 percent of estimated proved oil.
Lower Eocene and Paleocene	Gray shale with some sands that become thick and very permeable, particularly in Coalinga and southern border areas. Marine, with *Foraminifera* and megafossils.	5,000—6,000	
Upper Cretaceous	Upper part is purple-weathering and dark gray siliceous and calcareous foraminiferal shale and clay shale with local sands; middle and lower parts massive thick concretionary sandstone, conglomerate, and dark shale with intercalated sandstone. Marine.	25,000+	Small and local in more northern areas.

The sediments that form this thick stratigraphic section were derived by erosion from land areas occupying the present sites of the Sierra Nevada, the Tehachapi-San Emigdio Mountains, and the eastern Coast Ranges, and they were deposited in a comparatively small inland sea of shallow to moderate depth. Numerous different

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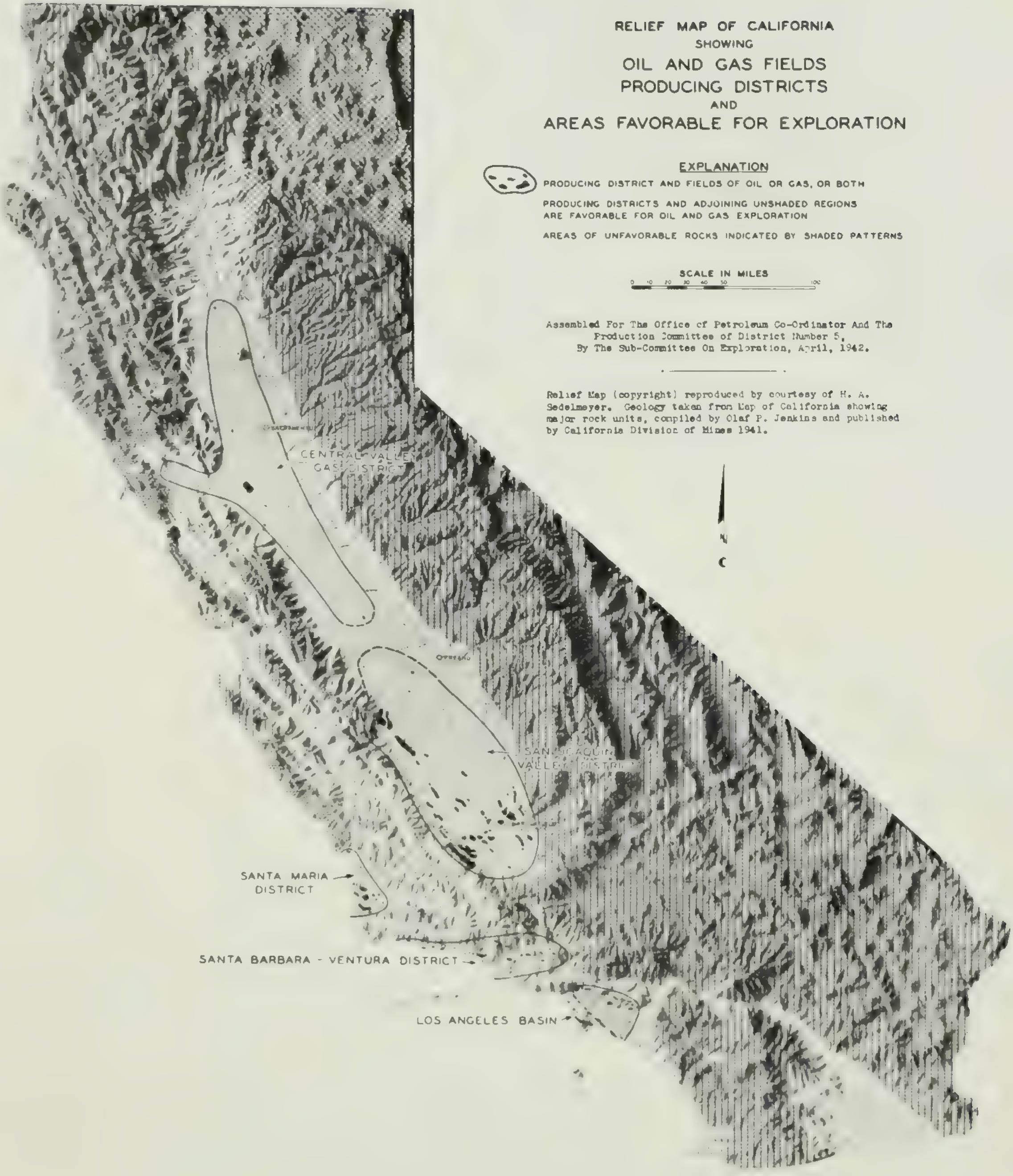
RELIEF MAP OF CALIFORNIA
SHOWING
OIL AND GAS FIELDS
PRODUCING DISTRICTS
AND
AREAS FAVORABLE FOR EXPLORATION
EXPLANATION
PRODUCING DISTRICT AND FIELDS OF OIL OR GAS, OR BOTH
PRODUCING DISTRICTS AND ADJOINING UNSHADED REGIONS ARE FAVORABLE FOR OIL AND GAS EXPLORATION
AREAS OF UNFAVORABLE ROCKS INDICATED BY SHADED PATTERNS
SCALE IN MILES
0
10
20
30
40
50
100
N
CENTRAL VALLEY GAS DISTRICT
SAN JOAQUIN VALLEY DISTRICT
SANTA MARIA DISTRICT
SANTA BARBARA - VENTURA DISTRICT
LOS ANGELES BASIN

Assembled For The Office of Petroleum Co-Ordinator And The Production Committee of District Number 5, By The Sub-Committee On Exploration, April, 1942.

Relief Map (copyright) reproduced by courtesy of H. A. Sedelmeyer. Geology taken from Map of California showing major rock units, compiled by Olaf P. Jenkins and published by California Division of Mines 1941.

FIGURE 1. Relief map of California.

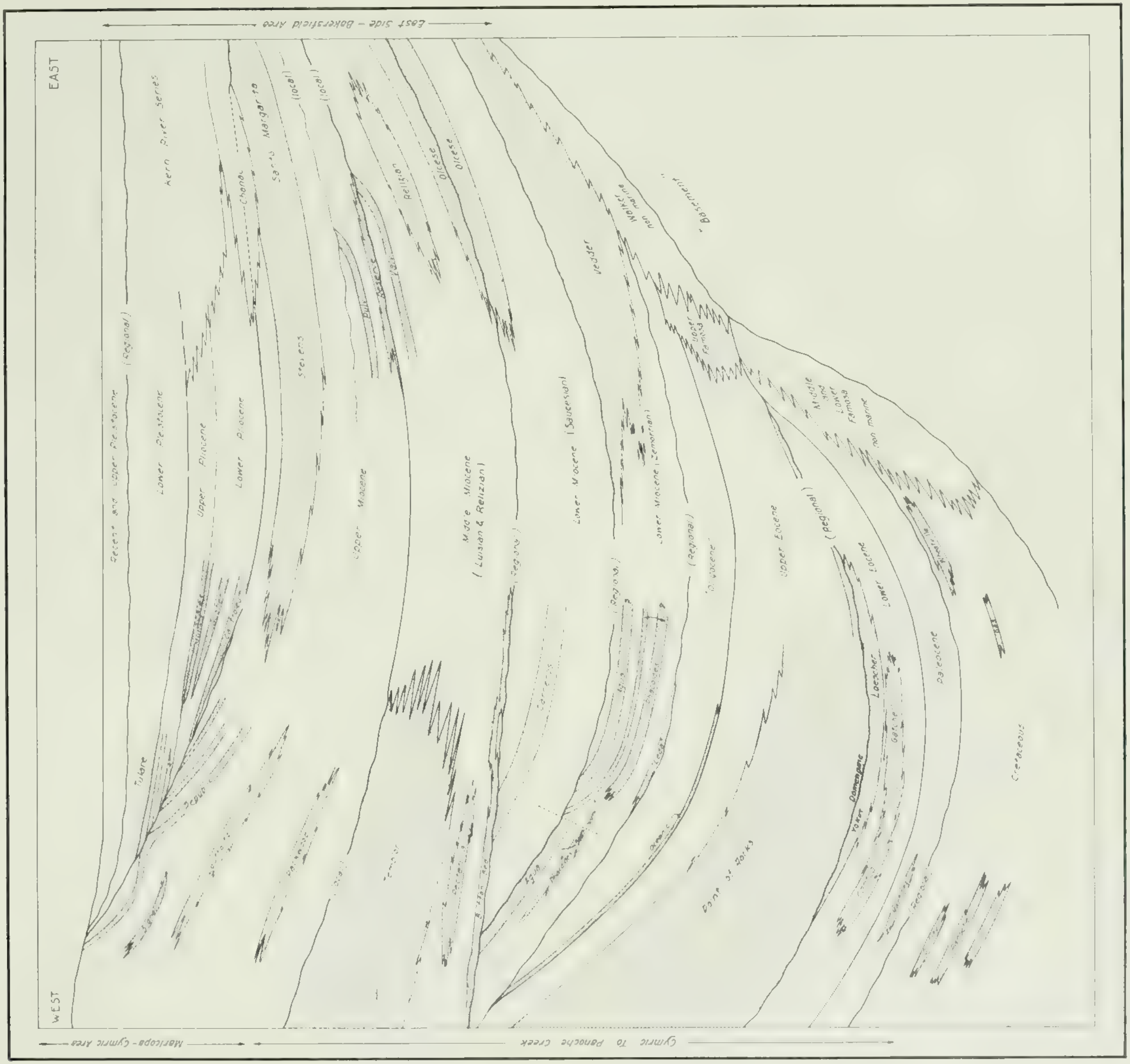

FIGURE 2. Diagrammatic chart of stratigraphy, San Joaquin basin.

lithologic facies accumulated contemporaneously. This inland sea occupied a basin that continued to subside in apparent response to the accumulating load of marine and nonmarine sediments, so that the only interruptions to deposition resulted from a series of tectonic events that affected not only land areas but parts of the basin as well. These tectonic events produced, within the already complex lithologic section of the basin, numerous unconformities that commonly increase the uncertainties involved in stratigraphic correlations.

The diagrammatic section (fig. 2) presents a simplified and schematic representation of the stratigraphic section. It is designed to emphasize the general relations of the major subdivisions of the section, as well as the positions and relations of the more important unconformities and sands, particularly those sands that serve as important reservoirs for oil and gas.

STRUCTURE

The San Joaquin basin of this report is the geosynclinal structure lying between the Temblor-Diablo mountain range and the Sierra Nevada. It extends northwestward from the San Emigdio-Tehachapi Mountains to the vicinity of Stockton, where a broad east-trending subsurface arch, herein called the Stockton arch, separates this basin from its northern structural counterpart, the Sacramento basin.

The accompanying small-scale map (plate 5) of all but the northern part of this basin is designed to emphasize only the more important structural features. Although the initial development of a few of these features dates from Eocene time, all of them, with the possible exception of the Stockton arch, attained their present structural form during and since the intense mid-Pleistocene orogeny.

The structure contours of plate 5 and the structure sections of plate 6 reveal that the geosyncline is highly asymmetrical, with its western flank the steeper, and that its principal axis lies west of the center of the basin. The comparatively gentle eastern flank is in reality the down-dip western part of the Sierra Navada fault block; its broad structural character has resulted principally from westerly tilt of this fault block throughout much of Cenozoic time. This eastern flank of the basin is further characterized by tension faults and by several gently folded anticlines.

The western flank and southern end of the basin, in striking contrast to the eastern flank, are steeply tilted, overturned, and intricately broken by thrust faults. These characteristics resulted from compressional forces that were active principally during the mid-Pleistocene orogeny, and there appear to be good reasons for believing that these same forces, or similar ones, also were responsible for appreciable lateral movement along the San Andreas fault during Quaternary time.

An additional characteristic of the western flank of the San Joaquin basin has influenced to a marked degree the accumulation of oil. Within the foothill areas of the Diablo and Temblor Ranges is a series of anticlinal folds that trend in directions slightly divergent to the regional strike, plunge southeastward into the basin, and provide numerous areas of local closure that have trapped oil. Several of these lines of folding are of major proportions, and they extend for miles as prominent structural features protruding into the Recent alluvium of the valley. Most prominent are the Coalinga-Kettleman Hills-Lost Hills anticline, Belridge anticline, Elk Hills-Coles Levee anticline, Buena Vista anticline, and the Pioneer anticline southeast of Maricopa. Most areas of closure along these folds are structural; others, such as East Coalinga and Guijarral Hills, are stratigraphic.

A major feature of the subsurface structure of the basin is the Bakersfield arch, which plunges westward from the Bakersfield-Fruitvale area to the Ten Section anticline. This broad arch is aligned in a general way with the Elk Hills-North Coles Levee anticlinal trend, and combines with it to form a continuous structural uplift which, in effect, divides the San Joaquin basin into two distinct sub-basins. The southern of these is referred to as the Maricopa basin, and the northern as the Tulare basin.

The Bakersfield arch is significant in another respect. It is a boundary that separates two somewhat different trends of folding. In the Tulare basin to the north, all major folds are aligned in a northwesterly direction, which approaches parallelism with the regional northwesterly strike of the basin; in the Maricopa basin, and including the Elk Hills-North Coles Levee trend, all folds are aligned in a more westerly direction and are more closely parallel to the regional westerly strike of formations along the southern end of the basin.

PALEOGEOGRAPHY

Geology Near the Beginning of the Tertiary Period

Development of the general structural form of the San Joaquin basin, as we know it today, had its beginning with a series of crustal movements during, and near the close of, the Upper Cretaceous period, and possibly continuing into the Paleocene epoch. These movements elevated Coast Range areas that previously were submerged by the Upper Cretaceous sea, and thus created the Diablo uplift. The ancestral San Joaquin basin* was thereby brought into existence as a restricted structural trough separating the Diablo uplift on the southwest from the older Sierran land mass lying to the northeast. It was in this trough, principally, that subsequent marine and nonmarine deposition throughout the Tertiary period was to expand and contract, in response to intermittent crustal adjustments, and to account for the development, along the borders of the trough, of numerous unconformities and sand pinch-outs that were to trap oil and gas.

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* For the pre-Tertiary history of central California, see Taliaferro (1951).

The accompanying paleogeologic map (fig. 3) is taken largely from Reed and Hollister (1936, fig. 5, p. 12), and portrays the approximate areal distribution of rock formations about the beginning of the Tertiary period. It shows the Diablo uplift at the beginning of Tertiary time as a land area composed of Franciscan (Jurassic and older ?) and Cretaceous rocks that extended from the San Francisco Bay district southeastward to the vicinity of Taft. This comparatively recent uplift was flanked on the southwest by additional land composed of granitic rocks, that is commonly believed to be older than Franciscan, and to have existed as a positive area throughout much of early Mesozoic and possibly also Cretaceous time. This old positive area of granitic rocks was named Salinia by Reed (1933, p. 12 and fig. 16).

The most striking geological feature shown in figure 3 is the apparent fault contact between the granite of Salinia and the Franciscan-Cretaceous rocks of the Diablo uplift, and the coincidence of this contact with the trace of the San Andreas fault as it exists today. Although Cretaceous rocks may not have been faulted, and may have covered more of Salinia than shown, considerable evidence permits the suggestion that the boundary between the granite of Salinia and the Franciscan rocks of the Diablo uplift may have been a fault of major displacement at the beginning of the Tertiary period. The thesis developed by Reed and Hollister (1936, p. 84) led them to postulate that "the northern part of the course of the San Andreas fault was marked out, though not necessarily followed by fracture, before the late Jurassic."

Cretaceous strata exposed along the northeastern border of the Diablo uplift rested unconformably on Franciscan sedimentary and igneous rocks. They consisted of marine sandstone, shale, and conglomerate, attained a maximum thickness exceeding 20,000 feet in the Coalinga district, and dipped gently northeastward beneath the ancestral San Joaquin basin, which at this time probably contained a remnant of the old Cretaceous sea.

The indicated presence of Cretaceous rocks along the southern extension of the Diablo uplift, in the area of the present Temblor Range and the southern Carrizo Plain, is conjectural. The granitic area of Salinia, with or without a Cretaceous cover, may have formed a continuous land connection in this district with the Sierran land mass * of granodiorite of late Jurassic age and older metamorphic rocks.

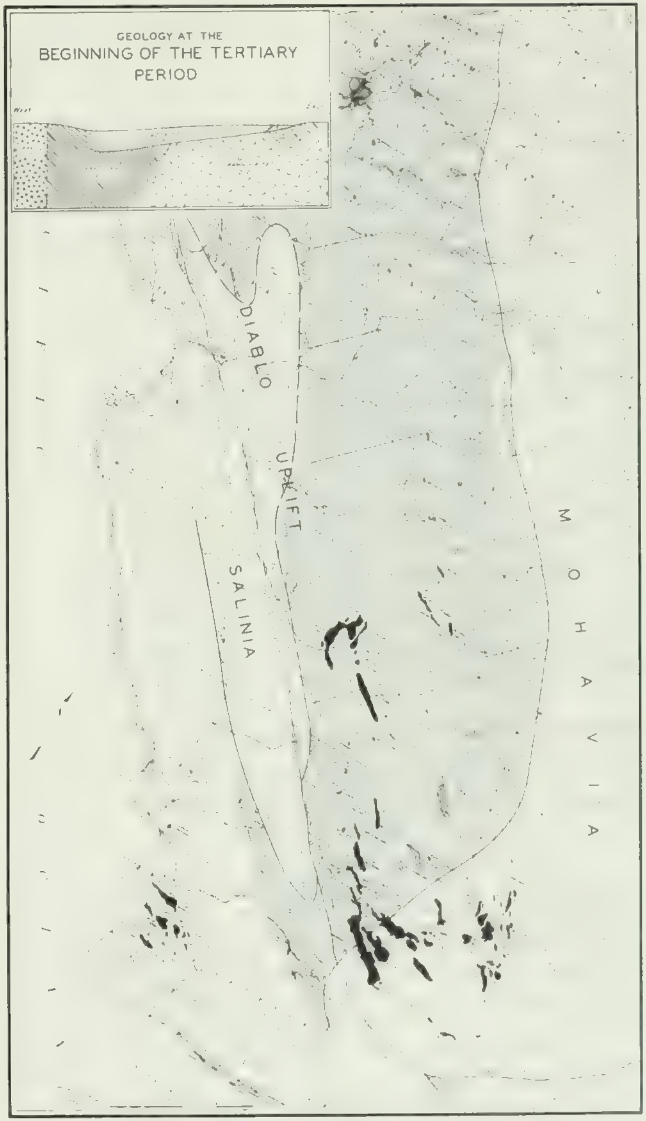

FIGURE 3. Geology at the beginning of the Tertiary period.

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* This name, as used in this paper, applies to the western part of Reed's Mohavia.

Land areas at this time presumably were moderate in topographic relief, for they contributed to early Eocene seas clastic sediments principally of fine to medium texture.

Paleogeography During the Tertiary Period

Lower Eocene. The distribution of the inland seas of early Eocene time, in which all Eocene (and Paleocene) marine sediments of pre-Domengine age were deposited, is believed to have been about as shown in figure 4. The San Joaquin sea extended north to Modesto and south to Wasco, and appears to have had a westerly connection with the open sea through the Vallecitos-San Benito Strait.

Northwest of Modesto and in the vicinity of Stockton, the absence of lower Eocene deposits in wells indicates that a 40-mile strip of lowland, the Stockton arch, separated the San Joaquin sea from another early Eocene sea that occupied the Sacramento basin to the north. Evidence, however, is not conclusive that lower Eocene sediments were not deposited over, and later eroded from, the Stockton arch.

The southern limit of the San Joaquin sea in early Eocene time is in doubt because of the absence of lower Eocene strata from outcrops in much of the Temblor Range, lack of subsurface data, and uncertainty as to the age of the oldest Eocene beds that crop out in the San Emigdio foothills between Santiago and San Emigdio Creeks. Any connection, if it existed, between the San Joaquin sea and the more southern early Eocene sea that occupied Lockwood Valley and the upper drainage of Sespe and Piru Creeks, probably lay west of Mt. Pinos.

The early Eocene closed with a marked regression of the sea that resulted from elevation of the Diablo uplift and from both elevation and folding of some basin areas previously submerged. The Helm anticline and folds of the Shale Hills area along the western border of the basin were formed at this time, raised above sea level, and deeply eroded.

Upper Eocene. Regional subsidence at the beginning of later Eocene time brought about an extensive marine transgression that rapidly covered areas not previously submerged since the post-Cretaceous orogeny.

Comparison of figures 4 and 5 illustrates the more widespread nature of the later Eocene sea for most parts of the San Joaquin basin. In addition to the general expansion of this sea, the previously indicated connection with the open sea through the San Benito trough is more definitely traceable, and there are suggestions that similar connections may have existed with the Sacramento sea to the north and the Ventura sea to the south. The southwestern

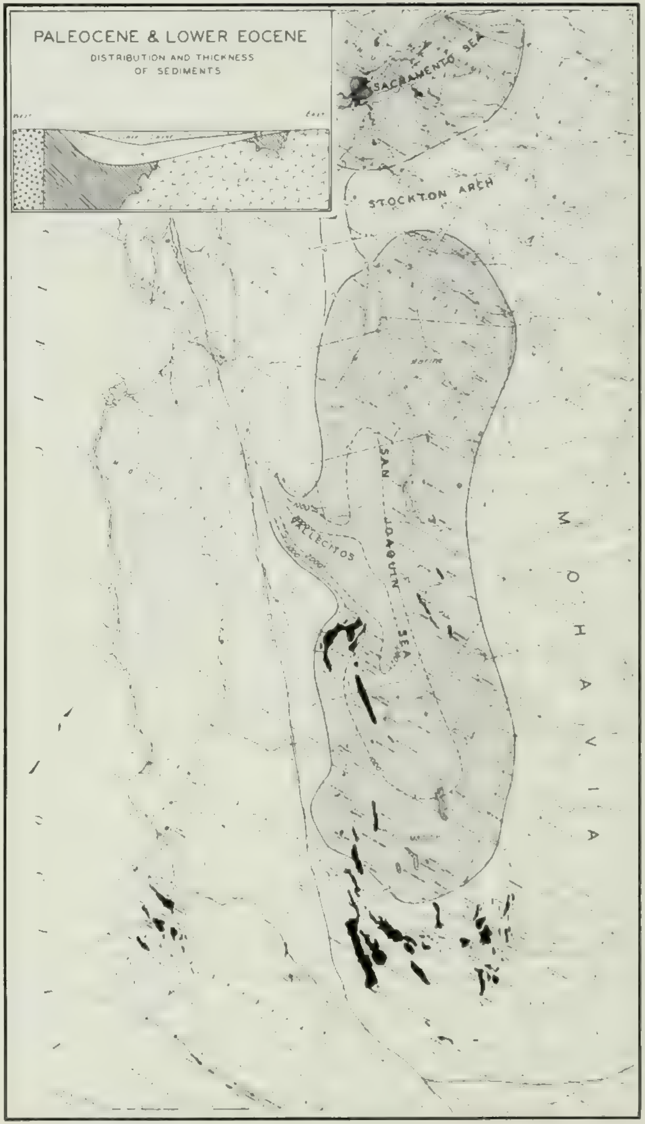

FIGURE 4. Paleocene and lower Eocene paleogeography.

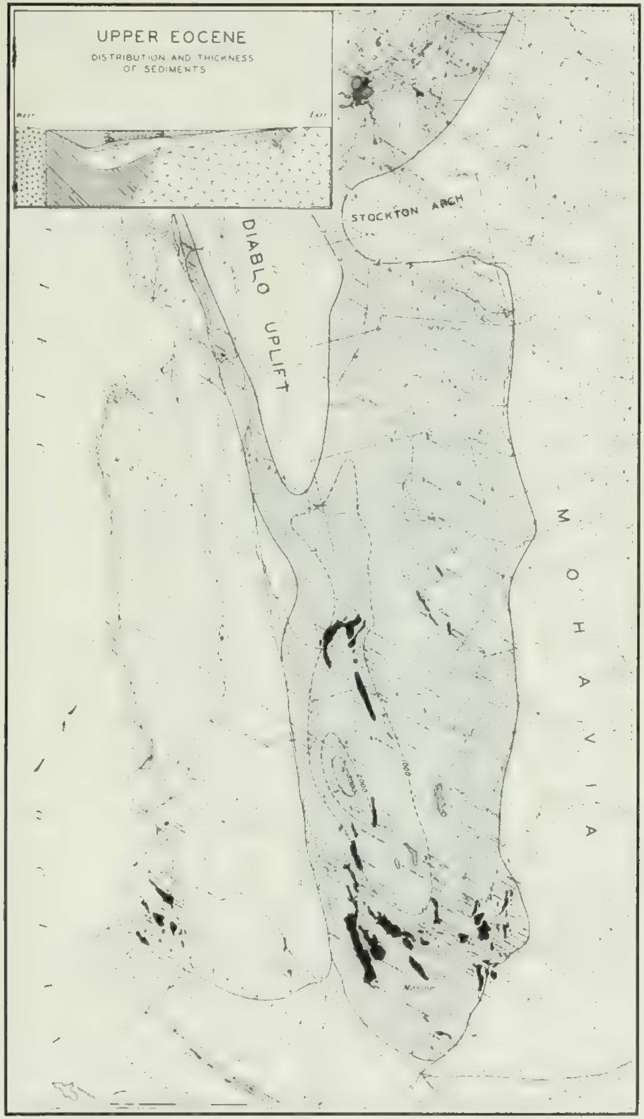

FIGURE 5. Upper Eocene paleogeography.

boundary of the San Joaquin sea, as well as the existence and position of the San Benito trough, appear to have been influenced by the ancestral San Andreas fault.

During the earliest brief stage of this transgression, a basal pebble bed, grit, or sand (Domengine) was deposited over previously elevated and eroded areas occupying much of the northern and western parts of the San Joaquin basin. A subsequent decrease in the coarseness of sediment supplied to the central and northern parts of the basin led to the accumulation of silt (Canoas) and an overlying thick series of organic and siliceous muds (Kreyenhagen) containing only local thin lenses of sand. Farther south, however, either lower topography or greater subsidence of the land, both along the western shore near Devil's Den and along the eastern shore near Famosa, permitted the sea to transgress extensive areas covered with deeply weathered lower Eocene soil. Here marine littoral deposits of Kreyenhagen time consisted principally of clean, well-sorted sand (Point of Rocks, Upper Famosa). Nonmarine green and red sediments (Walker) began to accumulate at this time in lowland areas adjoining the eastern shore.

"Oligocene" *. Regional uplift of much of California near the end of Eocene time affected land areas, such as Mohavia and the Diablo uplift, and elevated some basin areas (Ventura basin and the eastern border of the San Joaquin basin) previously submerged by Eocene seas. During "Oligocene" time, marine regression and the accumulation of continental deposits in old basin areas were more pronounced than at any other time in the Tertiary period (fig. 6). In the central part of the San Joaquin basin, however, marine conditions responsible for the deposition of the fine textured Kreyenhagen shale in later Eocene time continued into the "Oligocene" without appreciable interruption or change, and led to deposition of the lithologically similar Tumey shale.

The Tumey formation appears to have derived its scanty and fine-grained detrital material from the low-lying and deeply weathered land areas of Mohavia and the Diablo uplift. In the western part of the marine basin, sand was deposited as a thin interfingering lens at the base of the Tumey (Oceanic sand). Along the eastern border, Tumey muds graded shoreward into the upper part of the Upper Famosa sand. Toward the southern end of this sea, the fine siliceous

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* The Oligocene problem in California has been, and is, a subject of much uncertainty. The marine strata (Tumey) commonly classed as Oligocene in the central San Joaquin basin are conformable with, and similar in lithology to, the underlying Eocene strata, and are characterized by a foraminiferal fauna similar to that of the Jackson group (upper Eocene) of the Gulf Coast. It is reasonable to conclude, therefore, that they are of upper Eocene age. Marine Oligocene deposits are either thin or absent in the San Joaquin basin, or occur principally in that part of the stratigraphic section commonly, and herein, considered to be lower Miocene. To avoid confusion, however, this report classifies as "Oligocene" all those marine and nonmarine deposits to which this term is commonly applied by California geologists.

Tumey muds graded into a thicker section of sandy and argillaceous sediments that constitute the San Emigdio and Pleito formations ("San Lorenzo" group) of the San Emigdio foothills.

Much of the eastern border of the San Joaquin basin was above sea level during "Oligocene" time, and probably also during late Eocene time. South of Fresno the coastal land received deposits of variegated green and red beds ranging from a few feet, or tens of feet, of shale and sand (Walker) in the Bakersfield area, to several hundred feet of coarse conglomerate, sand, and shale in the Tejon Ranch-Salt Creek area (lower Tecuya).

The contact between "Oligocene" and overlying lower Miocene beds is marked in many localities by evidence of erosional unconformity with little or no angular discordance. It appears to represent a time of broad regional uplift, without important local folding, when the contracting "Oligocene" sea ultimately withdrew from most, if not all, of the San Joaquin basin.

Lower Miocene. Miocene time began with renewed subsidence of the San Joaquin basin, and with marine invasion of its southern half by way of a broad connection with the open sea that developed across southern Salinia and the Temblor Range (fig. 7). Subsidence of this Coast Range area appears to have eliminated, for the first time since the Cretaceous period, the influence of the San Andreas fault line on the distribution of seas. Elevation and rapid erosion of major land areas, particularly Mohavia and its Tehachapi-San Emigdio spur, contributed to the San Joaquin basin appreciable thicknesses of fine to coarse clastic sediments that were in sharp contrast to the siliceous muds of the preceding "Oligocene" and upper Eocene sequences. The general area of the Diablo uplift was land from western Kings County northward, but the absence of Franciscan detritus from lower Miocene sediments suggests that it was not deeply eroded.

Uplift of the Tehachapi-San Emigdio area near the beginning of Miocene time was associated with volcanism and the development, at the south end of the basin, of a series of basaltic and andesitic agglomerates and flows that form a conspicuous part of the upper Tecuya red beds (lower Miocene and "Oligocene"). This local volcanism accompanied the deposition of lower Miocene sediments in this area, and thus was considerably earlier than the large-scale volcanism that affected many parts of southern California during and near the close of middle Miocene time (see Shelton, Contribution No. 4, Chapter VII).

Marine deposits of the early lower Miocene (Zemorrian) consisted principally of well-sorted sand and silt along the east side of the basin near Bakersfield (Vedder sands) and in the Kettleman Hills area ("Vaqueros"). Basinward from these areas, the entire sec-

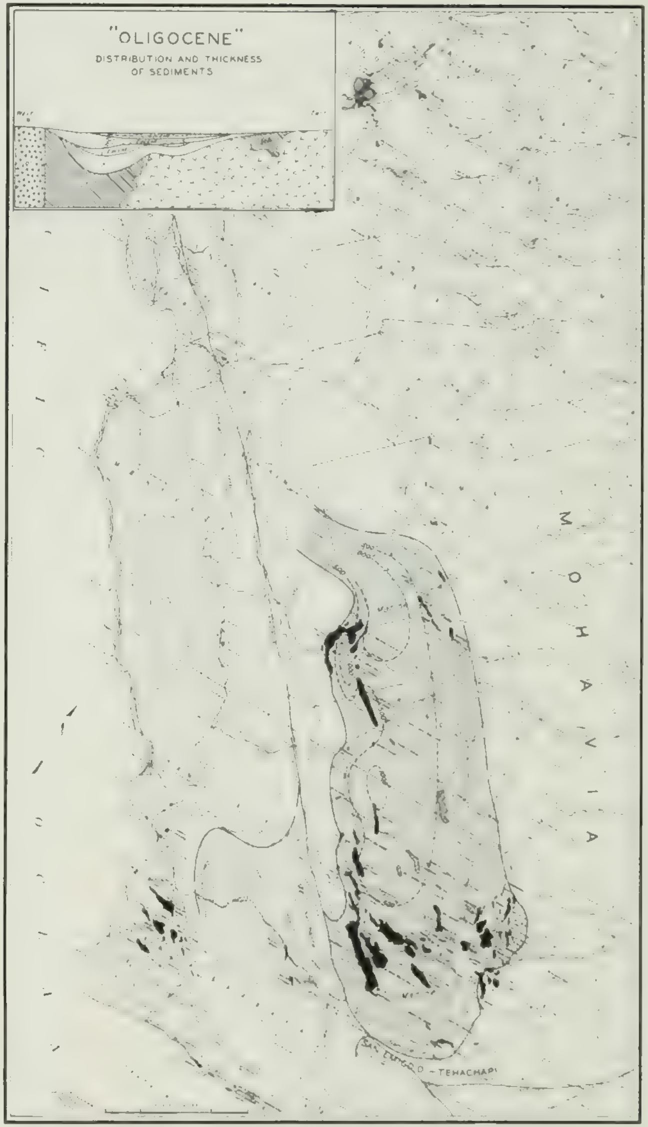

Figure 6. "Oligocene" paleogeography.

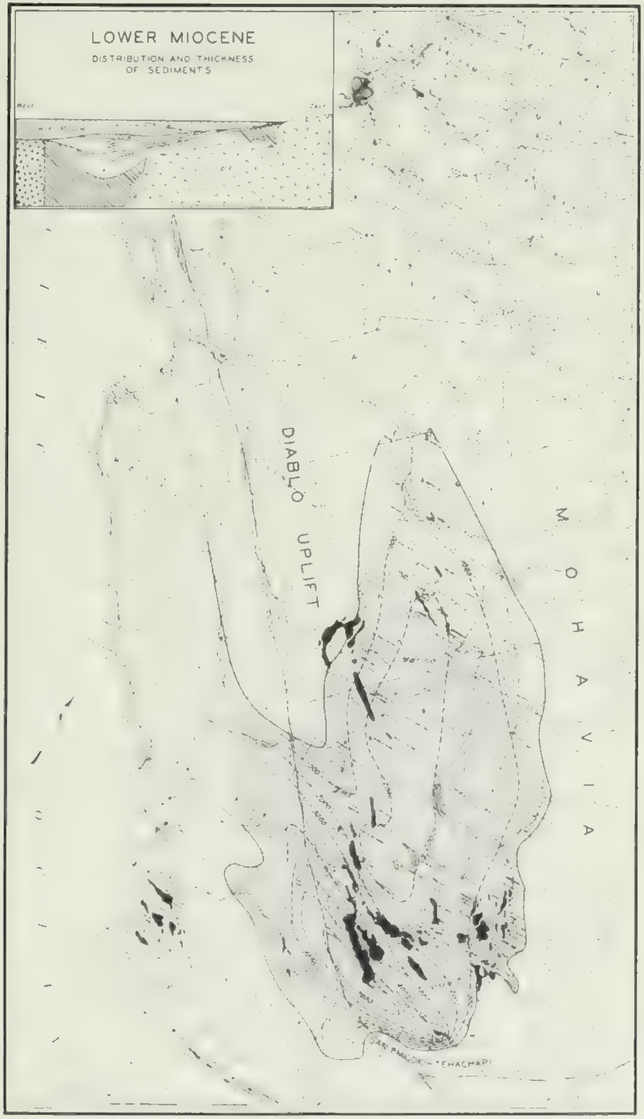

FIGURE 7. Lower Miocene paleogeography.

tion became thicker and graded into a series of interbedded sands (Phacoides and Agua) and argillaceous muds (Salt Creek and lower Santos shales).

Marine deposits during the latter part of the early Miocene consisted principally of silty and argillaceous muds (Freeman-Jewett, upper Santos, Whepley, Media) throughout most of the basin, but it included the Pyramid Hills sand along the eastern border, and, in the central and western parts, sands (Carneros, lower "Temblor") that apparently were derived, in part at least, from the Diablo uplift.

The latter part of early Miocene time was marked by uplift of Mohavia and by pronounced elevation and erosion of the southern part of the Diablo uplift and of previously submerged areas along its southeastern extension. This uplift of Mohavia, and the more rapid erosion of the land, produced a marked change in marine deposition from silt to sand (Olcese) in the eastern part of the San Joaquin basin before the end of the early Miocene, and permitted continued accumulation of nonmarine beds (upper Tecuya) in the Tejon Ranch area in the southernmost part of the basin.

Middle Miocene. Deposition of the marine Olcese sand in the eastern part of the basin continued without apparent interruption into the early part of middle Miocene time. At about this time the recently elevated and eroded southeastern extension of the Diablo uplift (fig. 8) was submerging and was being transgressed by marine sands (Button bed, upper "Temblor") and silts (Nonionella). Franciscan rocks of the uplift contributed appreciable amounts of detritus to these accumulating sediments, apparently for the first time during the Tertiary period.

Sands derived from the Diablo uplift thicken basinward toward Kettleman Hills and Belridge, where they and associated shales have a combined thickness of 1,000 to 1,500 feet. These sands, the Olcese sand to the east, and the younger "Valv" sands of the Arvin-Tejon Ranch area to the southeast, lens out completely toward a thick section of shale and silt that occupies the deeper parts of the basin.

The general subsidence and westerly marine transgression common to the southern Diablo uplift during the early part of the middle Miocene involved also the San Benito-Vallecitos trough, which had remained above sea level during early Miocene time. "Temblor" sands were deposited here across synclinally folded and truncated beds of "Oligocene" and upper Eocene siliceous shale.

Land areas were worn low by the erosion that contributed coarse sediment to the Button Bed and Temblor sands. During much of the remainder of middle Miocene time, streams delivered principally fine mud and silt which, with much organic matter, were widely distributed over the basin in thicknesses ranging from a few hundred to several thousand feet (Gould shale, Devilwater shale and silt, lower Maricopa shale).

Sediments accumulating in the northern part of the San Joaquin basin, north of southern Fresno County, were nonmarine and otherwise similar to those of the lower Miocene section.

In the latter part of the middle Miocene, pronounced local uplift of Franciscan rocks in the area immediately north of Coalinga contributed coarse detritus to the "Big Blue" formation and the equivalent "Upper variegated" zone of Kettleman Hills. Marine deposition along the eastern border of the basin was interrupted at the close of the middle Miocene by elevation and erosion of western Mohavia and adjoining near-shore areas that previously had been submerged.

Upper Miocene. Late Miocene time brought about renewed marine submergence of most areas previously covered by Miocene seas and, in addition, some parts of the Diablo-Temblor uplift that appear to have been land earlier during the Miocene (fig. 9). Old granitic land areas, such as Mohavia, its Tehachapi-San Emigdio spur, and parts of Salinia, were elevated and actively eroded to the extent that they contributed to the upper Miocene sea a large amount of coarse granitic sand. The disturbance at the close of middle Miocene time obviously was sufficiently widespread to create major changes in the identity and location of land areas.

This orogeny, affecting so materially the land areas, failed in some remarkable manner to cause any great difference in the distribution of the middle and upper Miocene seas. It created, however, new and unusual conditions of sedimentation within upper Miocene marine areas, which led to the deposition of a most heterogeneous group of sediments. Sharply contrasting facies of organic argillaceous mud, diatomaceous ooze, chert, sand, and conglomerate accumulated contemporaneously in different parts of the basin, and in some instances even those sediments having the greatest contrast, such as diatomaceous ooze and conglomerate, interfingered abruptly within local areas.

Coarse marine sand and conglomerate (Santa Margarita) and overlying nonmarine coarse detritus (lower Chanac) compose the entire upper Miocene section along the eastern border of the basin as far north as Fresno County. This marine sand is a near-shore facies deposited in a sea that, in much of this area, transgressed the truncated edges of middle Miocene strata. These upper Miocene beds thicken basinward from a few hundred feet to 6,000 feet, become entirely marine, and consist principally of organic shale (Reef Ridge, McLure, Antelope, Upper Maricopa) ranging in character from argillaceous to cherty and diatomaceous. Within the upper part

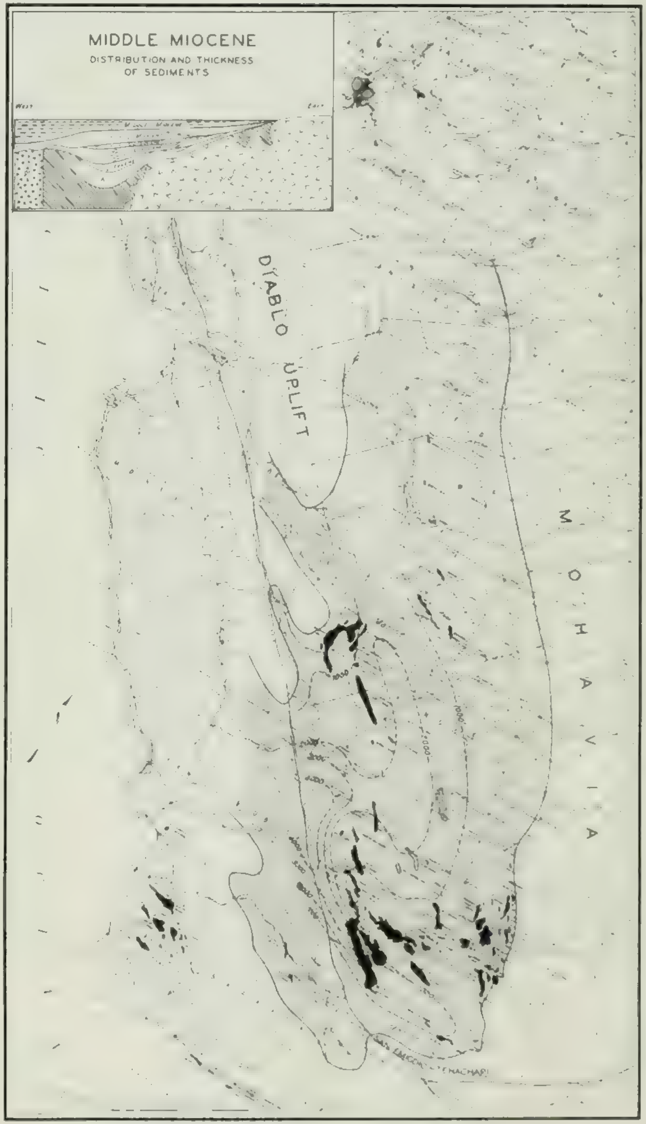

FIGURE 8. Middle Miocene paleogeography.

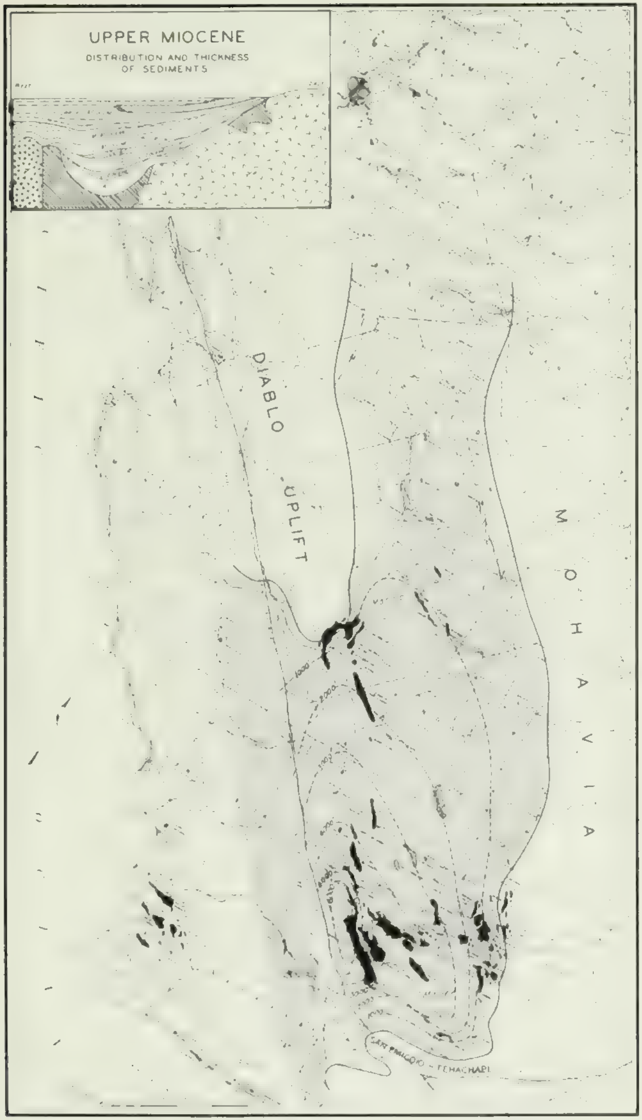

Figure 9. Upper Miocene paleogeography.

of this section are the several Stevens sand lenses, and in its lower part ("Pulv"* zone) are relatively thin lenses of "Pulv" sand. The detrital constituents of this westward thickening section, as far west as the central part of Elk Hills, were derived principally from Mohavia.

Other granitic sands and conglomerates farther west, notably the lenses of conglomeratic sands in the Temblor Range and the Santa Margarita conglomerate north of Coalinga and in the Cuyama Valley, hardly could have been derived from Mohavia; instead, it appears that they had their origin in the much closer granitic land areas of San Emigdio and Salinia.

The eastern border of the basin, extending from the Bakersfield arch south to the Tejon Ranch, was elevated and subjected to erosion in the early part of late Miocene time (end of "Pulv" time). The later upper Miocene marine transgression was terminated by an orogeny of pronounced regional and local effects, including elevation of the sea bottom and the development of land throughout the Temblor Range and extending westward and southward to include much previously submerged area of the southern Coast Range province. The much restricted San Joaquin sea was flanked on the southwest by upland connecting with the old granitic land mass of San Emigdio and extending north to the Coalinga area. By means of this uplift, the general structural outline of the San Joaquin basin as we know it today was almost completed, and Miocene sediments along the southern and southwestern borders of the basin were elevated and tilted basinward as much as 30 or 40 degrees. Uplift and accelerated erosion of Mohavia forced the Santa Margarita sea to recede gradually from the eastern border of the basin, and brought about the deposition of the coarse, ill-sorted nonmarine lower Chanac beds.

Pliocene and Lower Pleistocene. The earliest Pliocene (Etchegoin) sea of the San Joaquin basin occupied only the central and deeper part of the basin south of southern Fresno County, and had its connection with the open sea through the Priest Valley Strait northwest of Coalinga (fig. 10). Alluvial and lacustrine conditions (Chanac) continued to prevail along the eastern border of the basin, northeast and north of a strand line extending from points near Bakersfield to points not far northeast of Coalinga.

Subsidence of the borders of the basin and of adjoining land areas early in Pliocene time interrupted nonmarine Chanac conditions along the eastern border with the deposition of the Macoma shale (Etchegoin marine finger), and produced a general marine transgression along the southern and western borders. In these latter

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[*] *Pulvinunella gyrodinoformis*, a foraminiferal marker.

areas tilted and truncated Miocene shale, previously elevated and eroded, was gradually transgressed by Pliocene sediments. There was thus created one of the major unconformities of the California Tertiary, and the most pronounced and extensive stratigraphic trap for oil in the State. This regional unconformity, combined with favorable lithology and with local structure that was developed later, led to the accumulation of one and one-half billion barrels of oil in the west-side fields of the San Joaquin basin.

The marine transgression of the early Pliocene was terminated at the close of the Etchegoin (upper Mulinia) by regional uplift and gradual but persistent withdrawal of the sea. Some local areas of the San Joaquin basin, including the Buena Vista Hills, Elk Hills, McKittrick, North and South Belridge, and Lost Hills, appear to have experienced anticlinal folding at about this time. Thereafter, the basin continued to subside in relation to upland areas, but sedimentation along its eastern and southern borders became nonmarine and produced alluvial fans and typical alluvial and lacustrine deposits (Kern River, nonmarine San Joaquin clay). Contemporaneous deposition of marine San Joaquin clay in the central and western parts of the basin, including recently folded areas such as Lost Hills, Belridge, and McKittrick, terminated during late Pliocene time, and marine waters withdrew completely and permanently from the San Joaquin basin, except for a brief re-entrance of marine or brackish waters into the area of Kettleman Hills near the close of early Pleistocene (Tulare) time.

The marine sediments of Pliocene age (Etchegoin and parts of the San Joaquin formation) consist principally of silts, clays, and fine sands in the central part of the basin, but include numerous clean sands of medium to coarse texture along the borders. The lenticular nature of many of these sands, a result of their near-shore environment, made them ideal reservoir traps for oil and gas.

Continued elevation of upland areas and subsidence of the basin, from late Pliocene to middle Pleistocene time, brought about accumulation of thick and widespread lacustrine, alluvial-plain, and alluvial-fan deposits (Tulare).

EVOLUTION OF STRUCTURE

It seems to be generally agreed that oil was generated in source sediments contemporaneously with, or soon after, their deposition, and that the geologic structure of these and associated reservoir strata, from the time of their deposition to the present, was the dominant factor in determining the direction of oil migration and the locale of accumulation. It is of interest, therefore, to trace the evolution of the geologic structure now found in this thick section of petroliferous rocks.

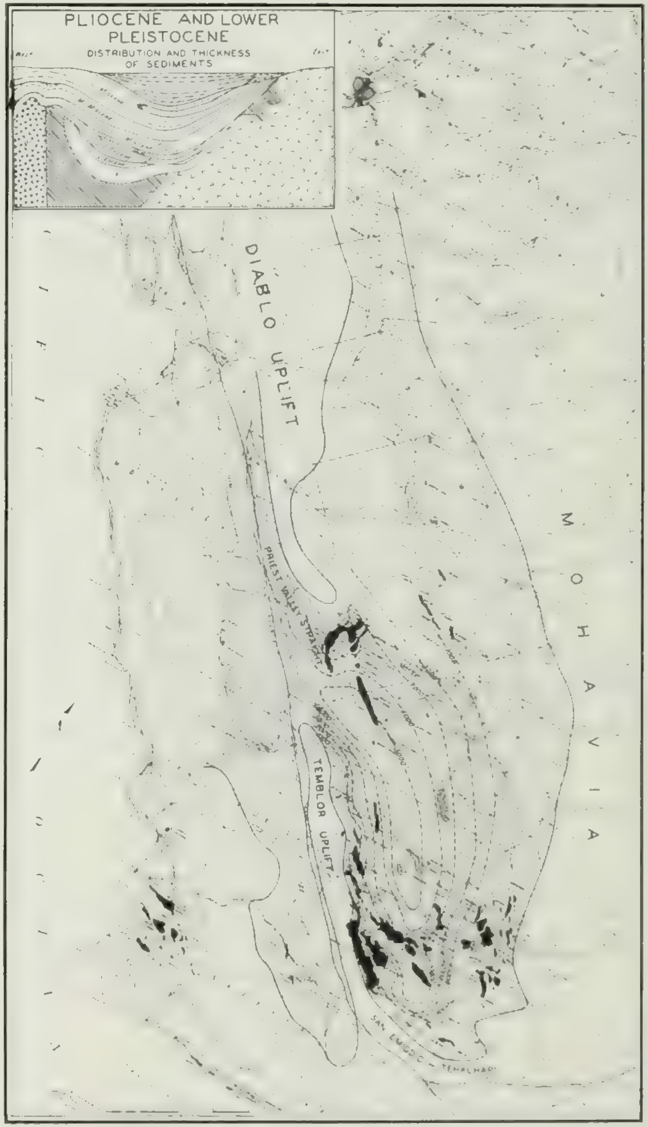


FIGURE 10. Pliocene and lower Pleistocene paleogeography.

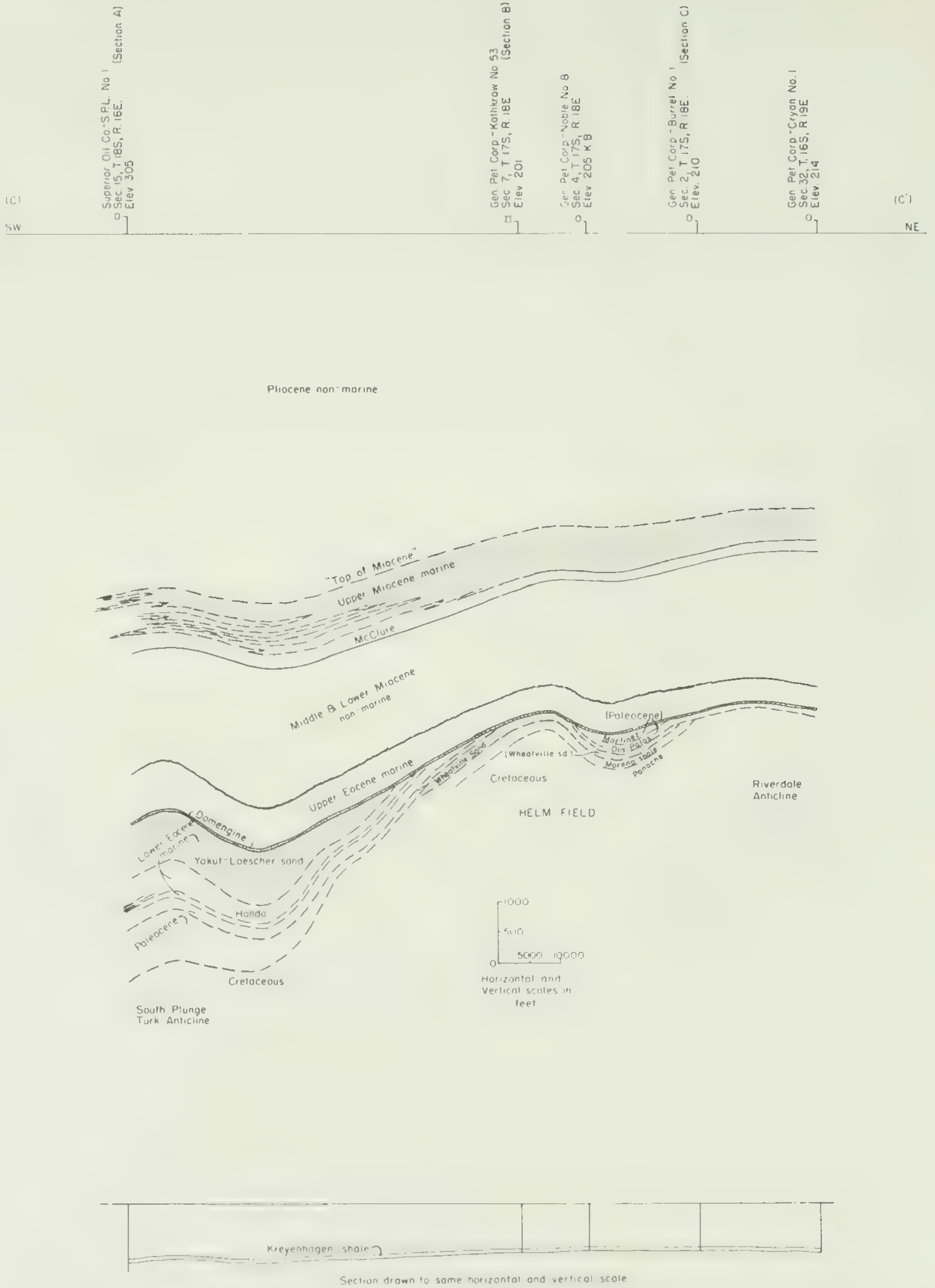
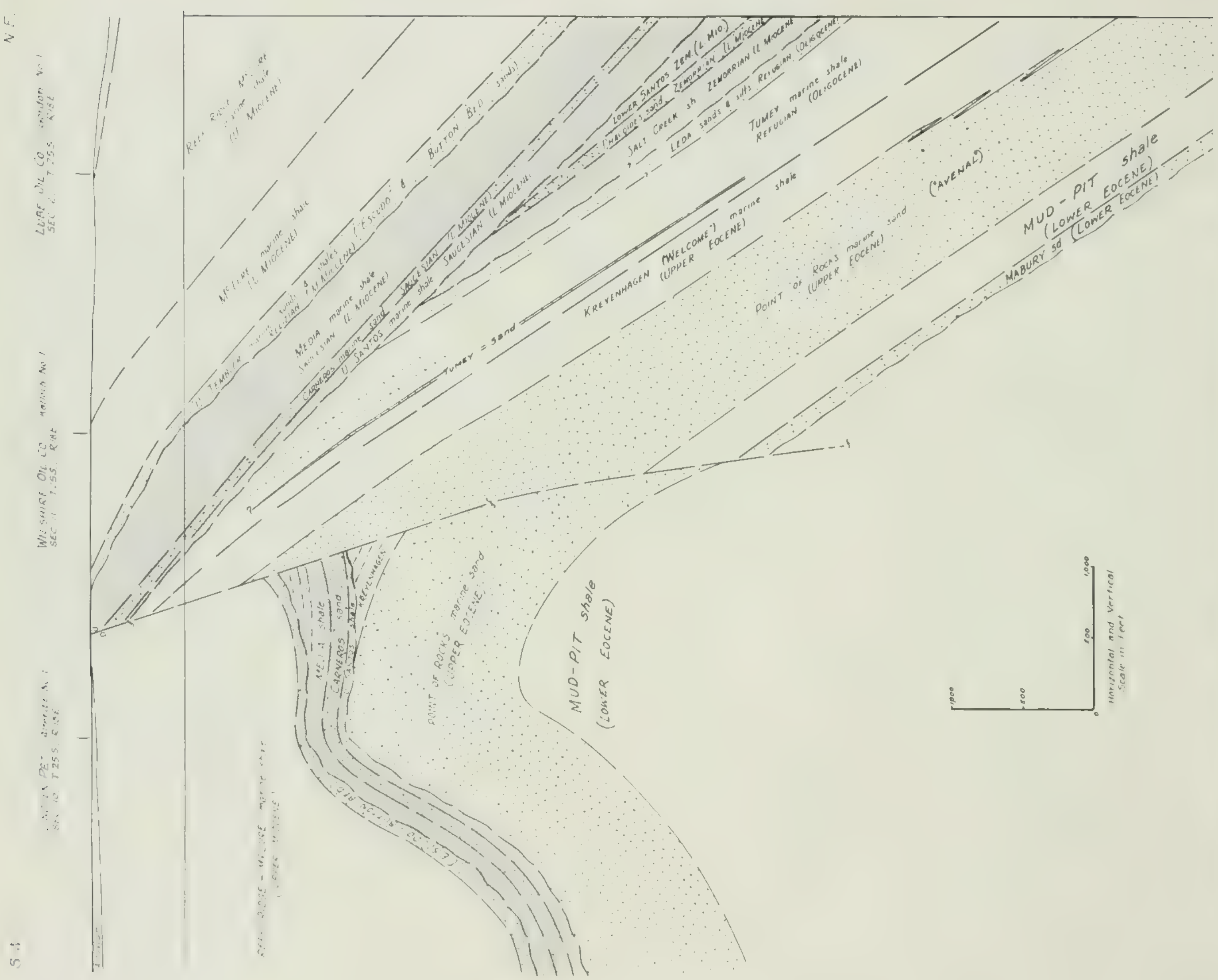


FIGURE 11. Structure section drawn from Turk anticline northeast across Helm anticline, showing middle Eocene unconformity at base of Domengine sand.


N.E.
S.W.
LUFE OIL CO. ... No. 1 SEC. ... T.25S. R.18E.
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... PET. ... No. 1 SEC. 10 T.25S. R.18E.
REEF RIDGE McLURE marine shale (U. MIOCENE)
McLURE marine shale (L. MIOCENE)
U. TEMBLOR marine sands & shales RELIZIAN (L.MIOCENE) ("ESCUDO" & BUTTON BED sands)
MEDIA marine shale SAUCESIAN (L. MIOCENE)
CARNEROS marine sand
U. SANTOS marine shale SAUCESIAN (L. MIOCENE)
SAUCESIAN (L. MIOCENE)
LOWER SANTOS ZEM. (L. MIO.)
"PHACOIDES" sand ZEMORRIAN (L. MIOCENE)
SALT CREEK sh ZEMORRIAN (L. MIOCENE)
LEDA sands & silts REFUGIAN (OLIGOCENE)
TUMEY marine shale REFUGIAN (OLIGOCENE)
TUMEY = sand
KREYENHAGEN ("WELCOME") marine shale (UPPER EOCENE)
POINT OF ROCKS marine sand (UPPER EOCENE) ("AVENAL")
MUD-PIT shale (LOWER EOCENE)
MABURY sd (LOWER EOCENE)
MEDIA shale
CARNEROS sand
SANTOS shale
KREYENHAGEN
POINT OF ROCKS marine sand (UPPER EOCENE)
MUD-PIT shale (LOWER EOCENE)
REEF RIDGE - McLURE marine shale (UPPER MIOCENE)
BUTTON BED (?)
1000
500
0
1000
500
Horizontal and Vertical Scale in Feet

FIGURE 12. Structure section drawn east across north Devil's Den area, showing the angular unconformity separating the upper and lower parts of the lower Miocene section.

The prevalence, during all of the Tertiary period, of substantial regional dips from the basin borders toward the deeper central basin area must have controlled in major degree the direction of regional migration of the oil that probably formed during the deposition and compaction of organic sediments. It appears to have led to the movement of billions of barrels of oil into up-dip areas such as Coalinga, Midway-Sunset, and Bakersfield. Available evidence indicates that other structural traps were present locally in the central basin area, where at least some anticlines began to grow as early as in late Miocene time.

Land areas adjoining the San Joaquin basin experienced intermittent uplift contemporaneously with subsidence of the basin deep. Many stages of uplift were comparatively minor, and served merely to produce slight changes in sedimentation, and/or local erosional unconformities in the stratigraphic section of the basin border. Others were pronounced but local, and resulted in unconformities with appreciable angular discordance. Still others were regionally pronounced, and resulted in unconformities extending for many miles into the basin of deposition.

Several of the unconformities that appear to mark important events in the structural evolution of the San Joaquin basin are discussed in the following paragraphs.

Middle Eocene Uplift. The Eocene unconformity at the base of the Domengine-Avenal sand is illustrated by the accompanying structure section (fig. 11) drawn northeastward across the Helm anticline. Except for the apparently regional disconformity in middle Paleocene time (base of Martinez), this basal Domengine unconformity marks the first major diastrophic event of the Tertiary period. Its effects appear to be more pronounced in the Helm area than elsewhere, but it is represented throughout the Coalinga-Panoche Creek area by a glauconitic sand or pebble bed at the base of the Domengine section.

Post-"Oligocene" Uplift. Regional uplift of limited magnitude near the close of "Oligocene" time elevated borders of the basin and produced an erosional unconformity with apparent local discordance between basal Miocene beds and the underlying "Oligocene" and Eocene sections. Disconformity without angular discordance along this contact on the western border of the basin is illustrated in the right-hand quarter of the structure section in figure 12.

Middle Lower Miocene Uplift. Local uplift of the Devil's Den-Pyramid Hills area, along the western border of the basin, occurred near the close of the Zemorrian stage. Angular discordance along the resulting unconformity is apparent in the right-hand half of the structure section in figure 12.

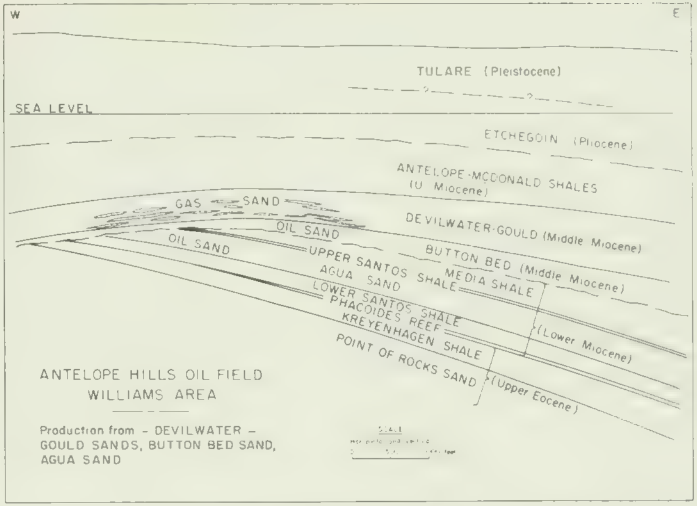

FIGURE 13. Structure section drawn east across Antelope Hills oil field, showing Button Bed unconformity at base of middle Miocene section.

Post-Lower Miocene Uplift. An unconformity at the base of the middle Miocene "Button Bed" extends throughout the Temblor Range-Reef Ridge district and areas basinward therefrom, and marks the most important tectonic event of the middle Tertiary. This unconformity, as it occurs in the subsurface, is illustrated in figures 12 and 13. Pronounced uplift and erosion near the close of early Miocene time was followed by marine transgression and deposition of the "Button Bed" sediments across the truncated edges of all older Tertiary formations.

Orogeny near the End of Miocene Time. As the result of a pronounced and widespread orogeny near the close of the Miocene epoch, extensive areas of the basin border that previously were submerged were elevated to positions above sea-level, and were tilted basinward. A new land area was thus formed along the southwestern border, and the San Joaquin basin was given a structural outline similar to that at the present time. Miocene beds along the southern end and western border of the basin were tilted basinward as much as 30 degrees, and subsequently were eroded to sea-level and were transgressed by Pliocene marine and nonmarine sediments. The importance of the resulting unconformity to oil accumulation in both Miocene and Pliocene beds is illustrated by the accompanying structure section across the Midway-Sunset oilfield (fig. 14).

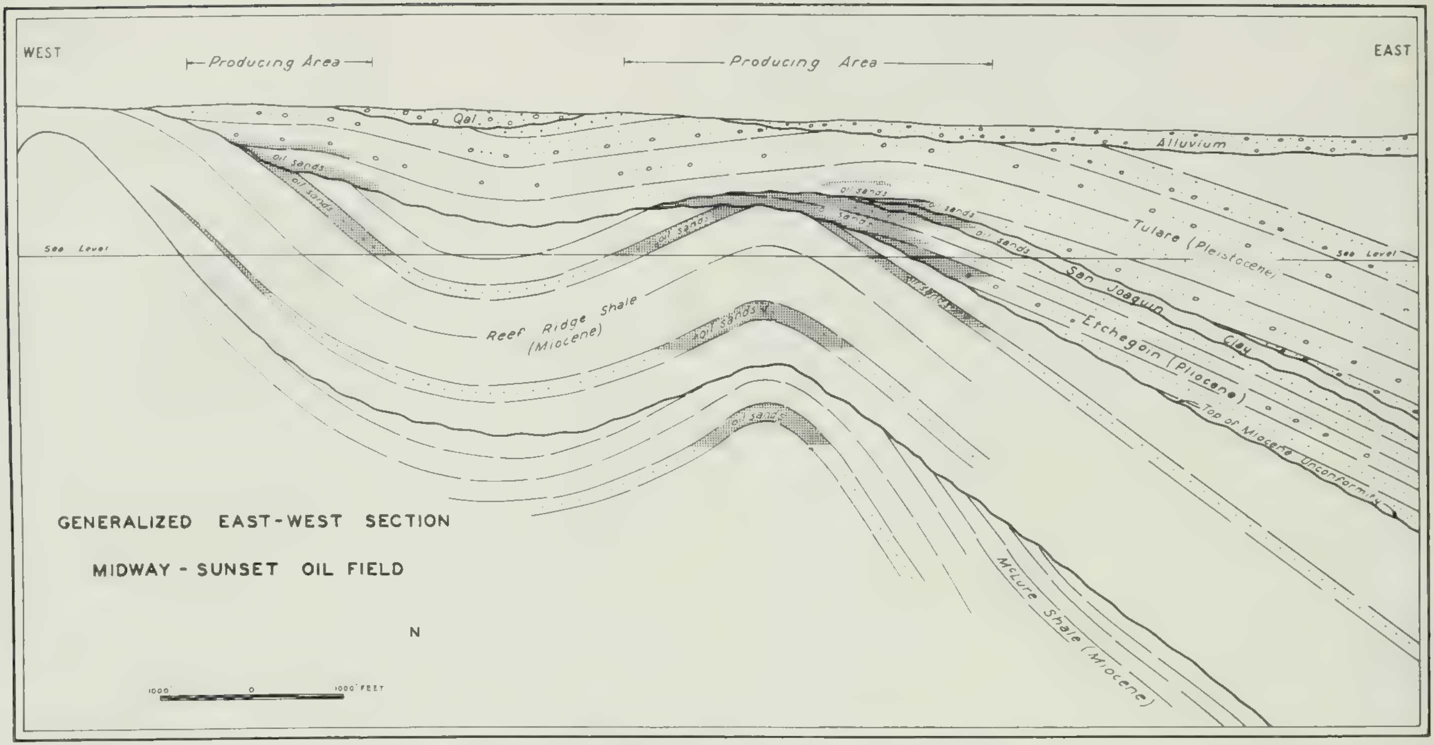

FIGURE 14. Generalized structure section across Midway-Sunset oil field.

Middle Pleistocene Orogeny. At the close of Tulare deposition, in mid-Pleistocene time, there occurred a pronounced orogeny, the magnitude and intensity of which exceeded that of any disturbance since the Nevadan revolution of the late Jurassic. It was this orogeny that expelled remaining small seas from several parts of California and produced, through folding, faulting, and subsequent erosion, most of the present structure and topography.

Most, if not all, of the anticlinal folds in the central San Joaquin basin, from the Coalinga nose to Paloma, were formed at this time, or at least were given the greater part of their present structural relief at this time. Sedimentary rocks of foothill and mountain areas, bordering the basin on the south and west, underwent pronounced uplift and compression that produced a complex pattern of sharp and overturned folds and thrust faults. In contrast, those of the eastern border experienced relatively gentle folding, tilting toward the basin, and tensional faulting.

Although it is certain that anticlines of the San Joaquin basin developed most of their present character and structural relief during the mid-Pleistocene orogeny, there is considerable evidence that some, and possibly most of them, began to develop as early as late Miocene or early Pliocene time, and experienced additional growth as broad, gentle folds during later Pliocene and early Pleistocene time. In some anticlines the timing of at least some of this early folding is indicated. In Lost Hills, for instance, an angular discordance of about 20 degrees occurs on the east flank between upper Etchegoin beds and the overlying basal San Joaquin formation. A similar angular discordance occurs higher in the section, at the base of what has been called Tulare lake beds in the axial part of the structure, but it is possible that these so-called Tulare beds actually are younger and were deposited after the mid-Pleistocene folding.

The structure-contour map (pl. 5) indicates the structural effects of this orogeny in the central part of the San Joaquin basin. That this orogeny may not have been completed in middle Pleistocene time is suggested by the occurrence during the late Pleistocene of several hundred feet of uplift in the San Emigdio foothills, and by the available physiographic and seismic record that California in general is still undergoing tectonic adjustment.

ACKNOWLEDGMENTS

The writers wish particularly to express their appreciation to the Humble Oil and Refining Company, and to Mr. Ed J. Hamner, Manager for this company in the California area, for permission to publish this paper. Most of the material contained herein has been taken, with some revision, from a larger report summarizing the results of a 3-year investigation of the geology of the San Joaquin Valley for the Humble Company.

One need only attempt a systematic study of a major California province that contains a representative section of Cenozoic and Mesozoic formations to appreciate adequately his indebtedness to such men as Ralph D. Reed, N. L. Taliaferro, R. M. Kleinpell, and J. S. Hollister. It is these men, and others of their time and earlier, who by their regional studies of stratigraphy, faunal sequence, and geologic history have eliminated much of the early conflict of thought and opinion concerning California geology, and who have revealed systematic order in its history.

Correlations of surface and subsurface formations, such as those in the accompanying structure sections of the San Joaquin Valley, are dependent to a large extent on age determinations by California paleontologists and stratigraphers working principally with foraminiferal faunas. In this regard the opinions and conclusions of R. M. Kleinpell, Stanley R. Beck, Frank B. Tolman, Paul P. Goudkoff, Boris Laiming, Wilbur D. Rankin, and Manley Natland have been particularly helpful.

The areal geology of upland areas bordering the southern part of the San Joaquin Valley, as shown on plate 5, is a generalized compilation of the published and unpublished work of many geologists. The generous cooperation of oil companies and geologists in providing base maps and records of exploratory wells is gratefully acknowledged.

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9. GEOLOGY OF THE TEHACHAPI MOUNTAINS, CALIFORNIA*

By John P. Buwalda†

INTRODUCTION

The San Joaquin-Sacramento Valley, also known as the Great Valley of California, separates the Coast Ranges on the west from the Sierra Nevada on the east. The southern part of this major physiographic and structural province is about 50 miles in average width, and is terminated abruptly at its southeastern end by the Tehachapi Mountains, a range that trends roughly northeast. Uplifted principally by faulting, this mountain mass rises boldly (fig. 2) from the floor of the San Joaquin Valley—a floor so smooth and so extensive that in early days it was referred to as the San Joaquin Plains. The range also presents a rather straight and imposing, though somewhat less formidable, front toward the Mojave Desert to the southeast.

The alluviated surface of the San Joaquin Valley lies only a few hundred feet above sea level, whereas the surfaces of the extensive coalescing alluvial fans built out into the Mojave Desert by the intermittent streams that drain the southeast slopes of the Tehachapi Mountains stand at elevations of 2,500 to 3,000 feet above sea level. The general altitude of most of the mountain mass is 4,000 to 5,000 feet, but several ridges rise above 6,000 feet and the dominating peak of the range, Double Mountain, reaches nearly 8,000 feet about 7 miles south of Tehachapi.

For many years the Tehachapi Mountains were regarded simply as the southern end of the great rigid, westward tilted Sierra Nevada block, but their structure, geological history, and origin are entirely different from those of the Sierra Nevada. Topographically the Tehachapi Mountains are continuous with the Sierra Nevada to the northeast, and form a connecting link between that range and the Transverse Range province to the southwest. They did not originate as an unbroken fault block tilted toward the San Joaquin Valley, but instead resemble a broad horst with complicated internal structure and with complex fault structure along its margins.

The northwest and southeast sides of the Tehachapi Mountains are rather sharply set off from adjacent provinces, mainly by fault scarps, but the end boundaries are topographically rather indefinite. The San Andreas fault southeast of Tejon Pass, and Grapevine Canyon north of the pass, form an irregular but convenient southwest limit of the range. The northeast limit on some maps is taken at Tehachapi Valley and Tehachapi Creek, the general route of the Southern Pacific Railroad and the Bakersfield-Mojave highway, but commonly included in the range is the mountainous country as far north as the south ends of Breckenridge Mountain, Walker Basin, and Kelso Valley. The northeast-southwest dimension of the range hence is roughly 50 miles, and its width increases from about 11 miles at the southwest end to about 30 miles at the indefinite northeast end.

Most of the range is in a semi-arid climatic belt that receives 10 to 20 inches of rainfall per year. The lower slopes and adjacent parts of the San Joaquin Valley and Mojave Desert are arid, and receive only a few inches of rainfall per year. The highest ridges and peaks, which constitute only a small fraction of the range, receive as much as 30 inches.

AREAL GEOLOGY

General Features

Upturned Tertiary formations crop out along both the northwest or San Joaquin Valley margin and the southeast or Mojave Desert margin of the Tehachapi Mountains, but more than 90 percent of the area of the range is underlain by pre-Cretaceous crystalline rocks (fig. 1). Some of these older rocks are metamorphic, but most are coarse-grained intrusive types. One area of Tertiary strata and associated volcanic rocks, several tens of square miles in extent, lies within the mountains northeast of Tehachapi Valley. These Tertiary strata, together with those exposed along the flanks of the range, shed much light on the later geologic history of the region and on the origin of the range. Unfortunately only a small fraction of the area has been mapped in detail, and hence no discussion of the geology can be made in more than general terms.

Pre-Cretaceous Sedimentary Rocks

Numerous patches of pre-Cretaceous metasedimentary rocks are scattered within the Tehachapi Mountains, but their aggregate outcrop area is only a small fraction of the total area of the range. They are well exposed on both the north and south sides of Tehachapi Valley, on the south side of the mountains about 9 miles west of Mojave and in areas farther west, and east of Tejon Pass, between Gorman and Lebec. They consist mainly of marbles, quartzites, slates, phyllites, and schists derived from both sedimentary and igneous rocks. The carbonate rocks have been burned for lime in the vicinity of Tehachapi during past decades, and are now being quarried for cement at Monolith.

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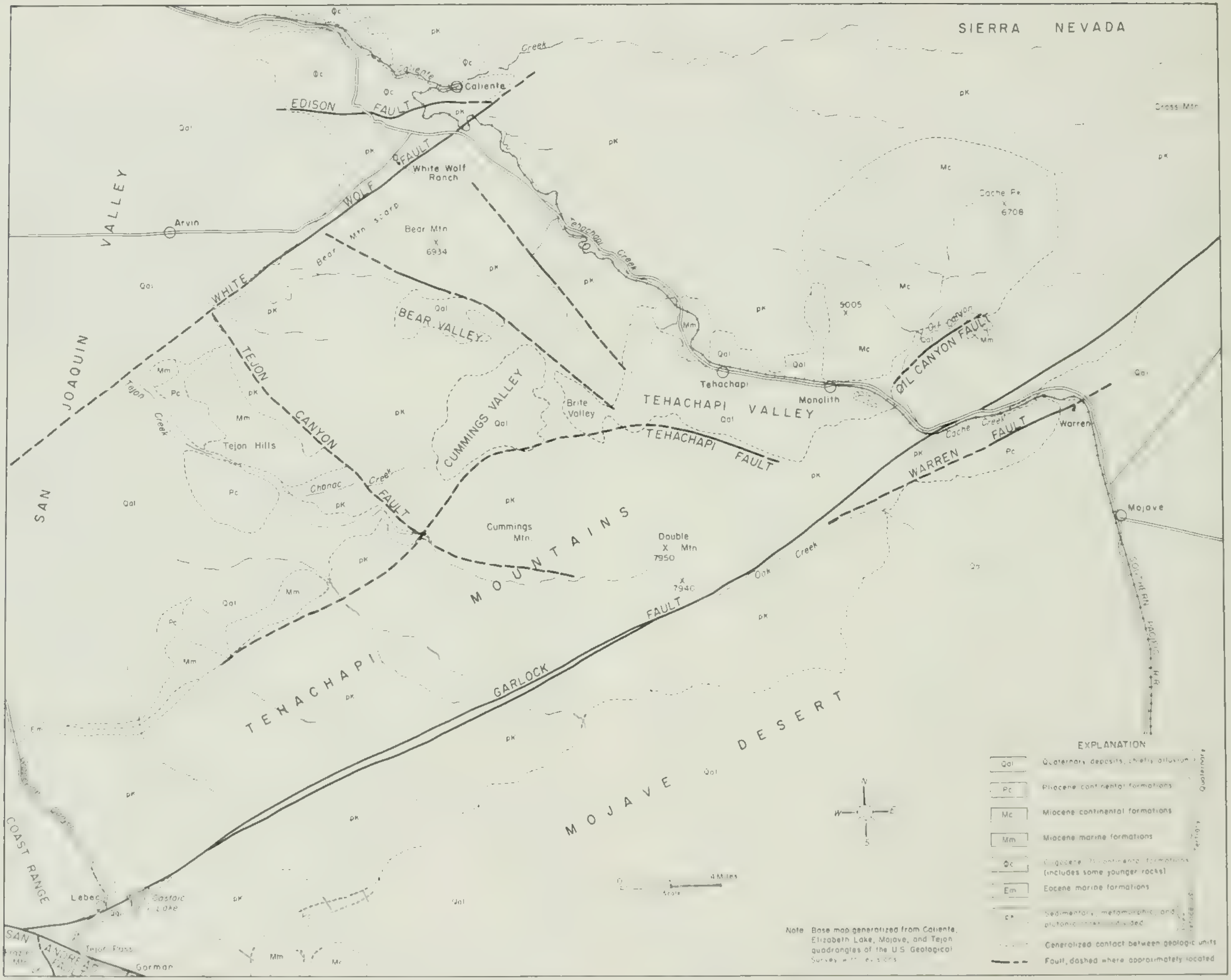

FIGURE 1. Geologic map of the Tehachapi Mountains.

The foliation in these metasedimentary and included igneous rocks ordinarily is parallel or nearly parallel to the bedding. The sedimentary section presumably corresponds to the Bean Canyon series of Simpson (1934) and to the Kernville series of Miller (1931) in the country farther north. On the basis of lithologic similarity, it has been considered as probably equivalent to the Calaveras formation of the middle Sierra Nevada, which usually is regarded as Carboniferous in age. Direct evidence of age of these beds in the Tehachapi Mountains consists only of supposed crinoid stems found by Goodyear (1888) on the south side of Brite Valley; they would indicate a Paleozoic or Mesozoic age.

The metamorphosed sediments occur in elongate patches as much as several miles in length, and with widths that generally do not exceed a mile or two. They commonly trend north to northwest. The strata themselves ordinarily strike roughly parallel to the long dimensions of the patches and dip at steep angles, but they are strongly deformed and commonly show small-scale folding, crumpling, and minor faulting. Thicknesses of several thousand feet can be measured, and the bodies clearly are remnants of a once-thick and important series of sedimentary formations that underlay the whole region; the remnants probably are mostly roof pendants.

Also present are scattered patches of still older metasedimentary rocks, mainly schists commonly associated with quartzites. One of the largest masses of these rocks is the strip of Pelona schist that lies between two branches of the Garlock fault and extends from a point near Lebec northeastward for a distance of more than 20 miles (Wiese, 1950). Its width is about 1 mile. These metasedimentary rocks are presumably pre-Cambrian in age.

Pre-Cretaceous Intrusive Rocks

By far the most extensive rocks in the Tehachapi Mountains are plutonic types of pre-Cretaceous age. They have not been studied exhaustively in any one district, but some general statements about them have been published by Goodyear (1888), Lawson (1904), Hoots (1930), Miller (1931, 1946), Simpson (1934), Miller and Webb (1940), Dibblee (1952, 1953), and others. For many years these intrusive rocks were thought to be a part of the great Sierra Nevada batholith, and to connect the old rocks of the Sierras with those of the Coast Ranges, but it now seems clear that, as in the Sierra Nevada farther north, the history of intrusion is far more complex than the emplacement of a single great molten body. The Tehachapi Mountains consist of numerous coarse-grained plutons of somewhat diverse mineralogical composition, of very irregular shapes and sizes, and of different ages.

Two general categories of older intrusive rocks can be recognized in the range. The younger of these includes the great bulk of the intrusives—rocks that range in composition from granite through monzonite, granodiorite, and quartz diorite to gabbro. The average composition is in the granodiorite range. These rocks are probably Jurassic in age, and correspond in general to the granodiorites of the Sierra Nevada. They are foliated in only a few areas, and are intrusive into metasedimentary rocks believed to be late Paleozoic in age.

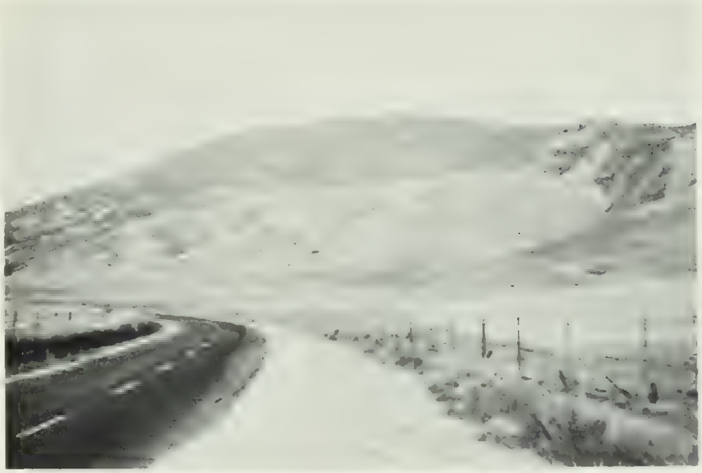

FIGURE 2. View eastward at northwest face of Bear Mountain, with floor of San Joaquin Valley in foreground. The entire face consists of pre-Cretaceous crystalline rocks. The violent earthquake of July 21, 1952, originated on a reverse fault along base of this scarp; the fault displacement created numerous ground ruptures along the trace, involving offsets of as much as a few feet.

An older group of scattered intrusive bodies is cut by the Jurassic (?) intrusives just described. In general they are more basic and commonly are gabbroic or dioritic. They also are more foliated. These rocks are intrusive into the late Paleozoic (?) strata, but their intrusion may have been in part contemporaneous with the deformation of that terrane. They probably are late Paleozoic or early Mesozoic in age. Some local masses of coarse-grained, commonly highly foliated intrusive rocks apparently are still older, and may be pre-Cambrian.

Tertiary Rocks within the Mountains

So far as is known, no Cretaceous formations of either sedimentary or igneous origin are present within or along the flanks of the Tehachapi Mountains.

Tertiary sedimentary strata, with associated lavas and pyroclastic rocks, occur within the mountains northeast of Tehachapi and north

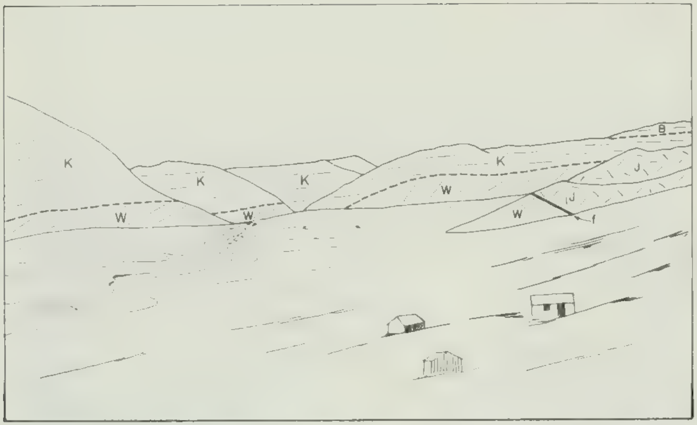

Figure 3. View northward up Cache Creek from a point about 1.5 miles east of Monolith. Beds of upper Miocene Bopesta formation (B) rest upon volcanic rocks of upper or middle Miocene Kinnick formation (K), which in turn rest with strong angular unconformity upon continental strata of lower Tertiary Witnet formation (W). Pre-Cretaceous crystalline rocks (J) have been thrust over overturned Witnet strata along a fault (f) of pre-Kinnick age. *Sketched from a photograph.*

of Monolith, where they underlie an area of perhaps 50 square miles. Three nonmarine formations, all at least moderately deformed, constitute this body of younger rocks; in order of decreasing age, these are the Witnet, Kinnick, and Bopesta formations.

Witnet Formation. The oldest of the three Tertiary formations, the Witnet, is the least widely exposed; it underlies an area of only a few square miles along Cache Creek and lower Oil Canyon about 5 miles northeast of Monolith. It consists mainly of beds, each generally a few feet thick, of coarse gray arkose alternating with thinner beds of dark sandy shale or siltstone. The arkose contains both angular fragments of volcanic rocks and locally numerous well-rounded pebbles and small boulders of quartz and quartzite. In general the materials are rather poorly sorted and the bedding is rude. The strata stand at steep angles, and are in part overturned. Their exposed thickness is not less than 4,000 feet, but neither the top nor the base of the formation is exposed.

In spite of repeated search, no fossil material of any kind has been found in the Witnet beds. Miocene strata lie with strong angular unconformity across their upturned edges (fig. 3), as is beautifully shown at the confluence of Oil Canyon and Cache Creek, and in turn they overlie the granitic rocks of the region. They appear to be much less lithified than the Cretaceous formations of the California Coast Ranges. Although they are distant from the nearest exposures of Sespe strata, they resemble some parts of this Oligocene Coast Range formation more closely than any other sedimentary unit. The Witnet formation is therefore of almost certain early Tertiary age, and may be Oligocene. Its arkosic character, the poor sorting of its materials, its rude bedding, the lack of fossils in it, and the angular form of its larger clasts indicate a continental, probably largely terrestrial, mode of deposition under arid or semi-arid climatic conditions. The numerous well-rounded quartz pebbles and cobbles, incongruous among arkosic and angular materials, presumably were derived in already-worn form from some older conglomeratic formation.

Kinnick Formation. In contrast to the underlying Witnet formation and the overlying Bopesta formation, the Kinnick formation consists largely of volcanic debris. It underlies an area of about 25 square miles north of Monolith, between Cache and Whiterock Creeks and along Sand Canyon. The beds that appear rather conspicuously in the hills immediately north of the cement plant at Monolith, and that are utlized to some extent in cement making, mark the southern end of this outcrop area of the Kinnick formation. A small isolated patch of sedimentary strata 1 mile to 3 miles northwest of Tehachapi probably was originally continuous with the upper part of the Kinnick section. Presumably the Kinnick beds extend southward and underlie the alluvium of at least part of Tehachapi Valley.

The formation consists mainly of green and other highly colored basic volcanic tuffs and some coarse agglomerates. Basic lavas constitute only a small part of the section. The upper few hundred feet of the formation consists of gray sandy clays that locally are interbedded with white fresh-water diatomite and gray and yellow cherts. The total thickness of the Kinnick is not less than 1,500 feet.

No fossils have been found in the pyroclastic lower and middle parts of the formation, but the sandy clay beds in the upper part have yielded the Phillips Ranch mammalian fauna. This fauna comprises several forms, including the genus *Merychippus* (Buwalda, 1916), and is presumably of middle or late Miocene age.

The Kinnick formation lies with strong angular unconformity upon the Witnet formation. It appears to be conformable with the overlying Bopesta formation, and is distinguished from it by a marked upward coarsening of the strata.

Some parts of the Kinnick section contain fossil leaves of deciduous trees, and also palm fronds. Much of the formation is well sorted and sharply stratified, and the sedimentary upper part is fine grained and water-laid. Some of these beds closely resemble playa deposits, and fossils representing several species of herbivorous mammals are found in them. It appears that the formation was deposited in a region of active volcanism and not very great relief, and under climatic conditions that probably were semi-arid rather than arid.

Bopesta Formation. The youngest of the three Tertiary formations, the Bopesta, is widely exposed in spectacular badlands (fig. 4) east of upper Cache Creek and 6 to 7 miles northeast of Monolith. It consists mainly of white to tan-colored, fine- to coarse-grained quartzose sandstone containing some ash and larger fragments of volcanic rock. Some beds are conglomeratic, and some gray sandy shale also is present. The formation extends northward under Cache Peak. It is moderately deformed (fig. 5), with dips up to about 30 degrees, and its thickness is not less than 3,500 feet.

Vertebrate fossil material has been found in some abundance in the lower and middle thirds of the section. Known as the Cache Peak fauna (Buwalda, 1916), it contains several mammalian species and is clearly of late Miocene age. It was previously thought that the Bopesta formation might be unconformable upon the Kinnick formation, because the dominant species of *Merychippus* in the Phillips Ranch fauna of the Kinnick formation is a small and apparently primitive form formerly thought to be of early Miocene age. This would mean that rocks of middle Miocene age are missing between the Kinnick and the Bopesta sections. More recent study of the Phillips Ranch fauna, however, seems to indicate that it is little older than the Cache Peak fauna, a conclusion that is compatible with the apparent structural conformity between the two formations.

Most of the constituent materials in the Bopesta beds are well rounded, and sorting in much of the formation is fairly good. Distinctness of bedding ranges from vague to sharp, the coarser material being in general the least definitely stratified. Cementation is highly variable; most of the strata are rather incoherent, but others are cliff-makers and aid in producing the very bold and picturesque badlands. The nature of the lithology and the vertebrate remains suggest deposition under semi-arid to humid conditions. Some of the materials apparently were lacustrine, whereas others probably were deposited by streams building up alluvial fans. The bouldery character of some of the coarse sandstone beds suggests considerable relief in the area that supplied the debris, and the generally rounded character of the debris and the paucity of arkosic material suggest a humid climate for those surrounding uplands.

Lavas and pyroclastic rocks, mainly of andesitic composition, overlie the Bopesta formation at Cache Peak and in some of the adjacent areas. Still younger are thin flows of olivine basalt 1 mile to 3 miles northeast of Monolith. They lie across the edges of the Kinnick formation, and probably are of Quaternary age.

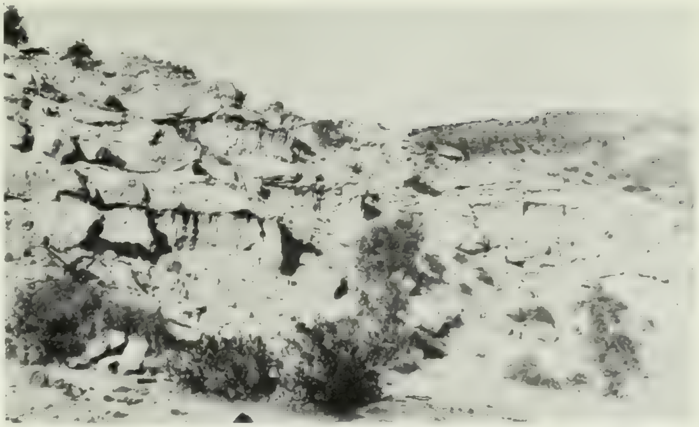

FIGURE 4. View northeastward at gently tilted continental upper Miocene strata of mammal-bearing Bopesta formation east of upper Cache Creek, south of Cache Peak.

Tehachapi Formation. On the north side of the west end of Tehachapi Valley, 1 mile to 3 miles west of Tehachapi, several hundred feet of a coarse fanglomeratic unit of probable late Pliocene or early Quaternary age, termed by Lawson (1906) the Techachapi formation, overlies gray tuffaceous shale, sandstone, and chert that probably are the equivalent of the upper part of the Kinnick formation. The Tehachapi beds dip toward the valley at about 10°; they are probably unconformable on the Kinnick(?) beds, which here dip somewhat more steeply. These fanglomeratic strata indicate that at least part of the development of Tehachapi Valley took place in later Pliocene or early Quaternary time.

Tertiary Geology along San Joaquin Valley Border

The Tehachapi Mountains present a bold northwest front toward the San Joaquin Valley from Grapevine Canyon on the southwest to Caliente Creek and the Southern Pacific Railway tracks on the northeast. This front consists of three segments. The two end segments, each about a third of the total length, trend northeast, and the somewhat shorter middle segment, east of the Tejon Hills, trends northwest. The entire front consists dominantly of pre-Cretaceous crystalline rocks, but Tertiary strata are exposed in strips a few miles in maximum width along the base. These sedimentary formations, commonly several thousands of feet thick, dip away from the mountains at moderate to steep angles, and the upper parts of the sections are concealed in many places beneath overlapping valley alluvium.

In the southwestern part of this bordering apron of stratified rocks, near Grapevine Canyon and the Coast Ranges, the Tertiary formations are mainly marine; northeastward along the mountain front, however, nonmarine beds and volcanic rocks become progressively more abundant. Near Grapevine Canyon the Tertiary section consists of several thousand feet of gray marine sandstone and siltstone (type section of the upper Eocene Tejon formation), above which are some hundreds of feet of Oligocene(?) land-laid beds (Tecuya formation). Resting upon these are several thousand feet of lower Miocene Vaqueros marine beds and a similar thickness of middle Miocene Maricopa marine diatomaceous shale. The Tecuya formation is unconformable on the Tejon, but in general the Tertiary section shows little angular discordance. The beds are steeply tilted and partly overturned at Grapevine Canyon, but farther northeast, toward Tejon Ranch, the northwesterly dips gradually decrease to moderate angles (Hoots, 1930).

In the Tejon Hills, about 15 miles northeast of the mouth of Grapevine Canyon, several hundred feet of middle Miocene marine strata rests unconformably on the pre-Cretaceous rocks at the base of the scarp. The strata dip moderately toward the valley, and thicken rapidly in that direction. Resting unconformably upon them are some hundreds of feet of upper Miocene marine Santa Margarita beds, which in turn are overlain without visible unconformity by Pliocene nonmarine strata of the Chanac formation, all dipping gently away from the mountains (fig. 6).

For about 8 miles north of the Tejon Hills no Tertiary formations crop out along the west base of the Tehachapi Mountains, but at Caliente Creek a strip of Tertiary strata several miles wide extends back into the range for a distance of nearly 10 miles to points beyond the town of Caliente (Dibblee, 1953). These strata, about 3,000 feet in thickness, have been dropped into the crystalline basement terrane by movement on the Edison fault, which bounds them on the south. The section consists of the Oligocene (?) Walker formation, the lower Miocene Ilmon basalt, the lower Miocene Freeman-Jewett shale, the Miocene Bena gravels, and the Pliocene Kern River gravels. Only the Freeman-Jewett shale, about 500 feet thick, is of marine origin. The bulk of the section is coarse grained, and some of it is dominantly volcanic in origin. The Pliocene Kern River gravels lie unconformably on the older Tertiary formations, and the Miocene strata have moderate to steep dips. Clearly this foothill belt experienced vigorous deformation in both Tertiary and post-Tertiary time.

Tertiary Geology on Mojave Desert Margin

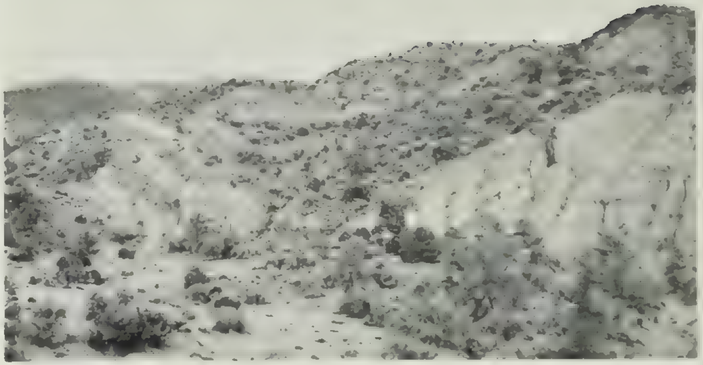

FIGURE 5. View northward toward upper Miocene continental strata of Bopesta formation south of Cache Peak, showing folding along northeast-trending axes.

Tertiary formations are exposed along a part of the southeast base of the Tehachapi Mountains. They are in part marine in the southwestern portion of the outcrop area, and wholly nonmarine farther northeast. In places they dip off the older rocks of the range and under the alluvium of the Mojave Desert, and in places they have been faulted down against the basement rocks.

Near Quail Lake, in the southwestern portion of the Mojave Desert front of the range Crowell (1952) and Wiese (1950) have mapped several thousands of feet of upper Miocene Santa Margarita formation, consisting of marine sandstone, conglomerate, and shale, and extending for about 4 miles northeastward from the San Andreas fault. Miocene continental deposits, presumably 5,000 to 8,000 feet thick, overlie the Santa Margarita and extend about 10 miles northeastward from the fault. These beds may be in part little different in age from the Santa Margarita section. Pliocene fresh-water lake beds, mainly siltstone, clay, and marl, also crop out along the southeast foothills of the range for about 8 miles. They may be in part equivalent to the upper part of the Miocene continental deposits, and have a maximum thickness of approximately 5,000 feet. Pleistocene terrace deposits and alluvium as much as several hundred feet thick lie unconformably upon all the older formations. Dipping from a few degrees to as much as 25 degrees, they record Quaternary tilting and faulting along the southeast flank of the range.

No Tertiary formations are known along the desert margin of the Tehachapi Mountains for a distance of about 20 miles northeast of the Tertiary exposures just mentioned, but a few miles northwest of the town of Mojave a strip of land-laid sediments appears along the south side of the east-west ridge that lies south of the railroad

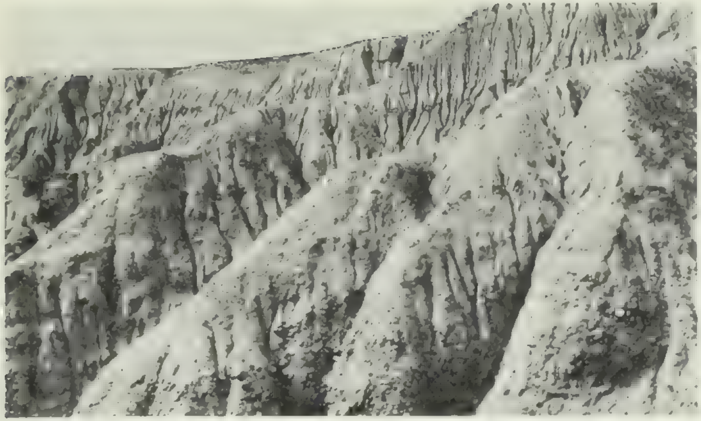

FIGURE 6. Typical badland exposure of continental lower Pliocene Chanac formation in Tejon Hills. The beds dip gently toward the San Joaquin Valley.

and lower Cache Creek. These strata often have been referred to as the Warren beds or Warren formation. They have been dropped down against a ridge of crystalline rocks along an apparently normal fault; the Garlock fault lies north of the ridge. The beds consist mainly of arkosic sandstone with one or more thin layers of volcanic ash. The total thickness exposed is several hundred feet. Vertebrate fossil remains indicate that the strata are approximately early Pliocene in age, and hence the equivalent of the Ricardo beds. They are gently to moderately folded.

No Tertiary strata occur along the southeast base of the range for 20 miles beyond the patch of Warren beds northwest of Mojave. At Jawbone and Redrock Canyons, still farther northeast, are extensive exposures of the Ricardo formation, consisting of about 7,000 feet of lower Pliocene terrestrial sandstone, conglomerate, and siltstone, with volcanic rocks. This section has been faulted down along the base of the eastern part of the Tehachapi Mountains and along the El Paso Mountains, and has been tilted northwestward at angles of about 30° by the uplift of the latter range (Dibblee, 1952).

STRUCTURE

Pre-Cretaceous Structural Features

The structure in the patches of pre-Cretaceous stratified rocks that are scattered through the Tehachapi Mountains is diverse, but is not yet well known. Elongate strips of Paleozoic (?) limestone and quartzite north of Tehachapi Valley commonly trend north to northwest, and the strata stand at steep angles; many exceptions are known, however, especially in the smaller patches. In the El Paso Mountains immediately to the east, Dibblee (1952) has described Permian strata with an apparent thickness of 23,000 feet that likewise trend north to northwest. Farther north, in the Kern River area, are inliers of old sediments with similar trend.

These formations, which have been intruded by the Mesozoic granitic rocks, probably were folded during Nevadan or Jurassic time, along with the pre-Cretaceous sedimentary formations of the Sierra Nevada farther north. Thus the area of the Tehachapi Mountains may well have been a part of the original Sierra Nevada. On the other hand, along the Garlock fault north of Mojave and at certain other localities, elongate strips of old rocks trend east to northeast, or roughly parallel to the Garlock fault. These features suggest that the east-west structural trend exhibited in the Transverse Range province to the south and southwest may have been initiated long before Tertiary time.

Tertiary Structural Features

The present Tehachapi Mountains are a product of Cenozoic deformation. The range is bounded on both sides by complex fault zones and by strips of sharply upturned Cenozoic formations. It is not merely an anticlinal arch, but is a complex horst, with both faulting and warping at its margins.

Structure along San Joaquin Valley Margin. As already noted, the northwest margin of the Tehachapi Mountains comprises two end segments that trend about N. 50° E., or roughly parallel to the Garlock fault on the opposite side of the range, and a third or intermediate segment that trends at right angles to the other two. These three divisions of the San Joaquin Valley front are determined by separate structural features of somewhat different type.

The northeast segment, extending for about 15 miles northeastward from the Tejon Hills to points beyond Caliente Creek and the Southern Pacific Railroad, is determined by the active White Wolf fault. It was on this break that the Arvin-Tehachapi earthquake of July 21, 1952, occurred; this was one of the strongest shocks in southern California since 1857, and the strongest in the entire State since the San Francisco earthquake of 1906. The fault lies along the base of the spectacular northwest-facing Bear Mountain scarp, which is about 5,000 feet in height. Extensive geological, seismological, and geodetic studies in connection with the 1952 earthquake indicate that the fault is of reverse character, dipping southeastward under the mountains at a probable angle near the surface of 45° ± 15°. Northeast of the Tejon Hills the fault is bounded on both sides by pre-Cretaceous crystalline rocks, except at Caliente Creek, where small masses of Bealville conglomerate, considered by Dibblee (1953) to be of Oligocene age, have been dropped down against the older rocks along the fault. At the Tejon Hills the folds in the Tertiary formations, the youngest of which is the Pliocene Chanac, are apparently cut off by the fault, which continues southwestward beneath the Quaternary alluvium of the San Joaquin Valley for about 15 miles to Wheeler Ridge or beyond.

The epicenter of the 1952 earthquake was on the south side of Wheeler Ridge. Northeastward from this ridge, geophysical exploration by the Richfield Oil Corporation demonstrates that the total offset of the basement surface along the White Wolf fault is about 10,000 feet. Geodetic work by the U. S. Coast and Geodetic Survey indicates that northeast of the Tejon Hills the upper side of the fault moved northward 2 to 3 feet horizontally and rose about 2 feet, while the northwest side sank about the same amount in connection with the recent earthquake, but the points of both maximum uplift and subsidence were several miles from the fault, with apparently no sharp vertical offset at the fault. The recent fault movement was therefore presumably oblique slip, but mainly dip slip. West of the Tejon Hills the horizontal displacements of triangulation points were comparable in magnitude but entirely different in direction, being mainly westward on both sides of the fault; unfortunately, only one point was located on the lower block. The vertical change here was also about 2 feet on each side, with the maximum subsidence again occurring several miles northwest, and the maximum uplift several miles southeast, of the fault.

The White Wolf fault developed no fresh traces of displacement on the San Joaquin Valley alluvium during the recent earthquake. Northeast of the Tejon Hills tremendous landsliding on the Bear Mountain scarp during past centuries has produced a topography and a macerated rock mass across the approximate trace of the fault such that only numerous disconnected soil ruptures of very diverse trends and amounts and directions of offset were formed. However, several huge new cuts, developed during revisions of four Southern Pacific Railroad tunnels that were damaged by the earthquake, revealed at least three fractures in the bedrock. Taken to be branches of the fault, these breaks dip 30° to 45° southeastward and under Bear Mountain.

The middle segment of the San Joaquin Valley front of the Tehachapi Mountains trends northwest. The great scarp rising from the White Wolf fault turns a right angle at the Tejon Hills, and continues southeastward, with a height of about 2,000 feet, along the northeast side of Tejon Creek canyon practically to the summit of the range. The presumed fault responsible for this scarp was termed the Tejon Canyon fault by Hoots (1930). There is little structural evidence for this fault except near its northwest end, where at one locality Santa Margarita beds butt against older granitic rocks. The Tertiary formations of the Tejon Hills in general lie with depositional contact on these granitic rocks, but dip away from the mountains at angles of 10° to 50°. The boldness of the scarp, and the sharp topographic boundaries between it and the Cummings Valley upland above and the Tejon Valley below, indicate either a northwest-trending fault or a very sharp warp, or a combination of the two, developed in post-Chanac time.

The third or southwest segment, closing in the extreme southeast end of the San Joaquin Valley, extends from Tejon Creek to Grapevine Canyon. At the mouth of this latter canyon, upper Eocene Tejon strata stand at very steep angles or are overturned toward the valley. Hoots (1930) showed probable fault relations here, and, considering the prevalence of reverse and overthrust faulting west of Grapevine Canyon, the boldness of the scarp of old rocks that rises above the Tertiary formations, and the overturned structure of the Tertiary beds, it is almost certain that strong reverse or overthrust faulting has occurred here and for some distance to the east.

East of Grapevine Canyon, the Miocene strata, finally lying in depositional contact on the older rocks, dip less and less steeply as they are traced toward the Tejon Ranch headquarters. But as far as Tejon Creek the steep bedrock front, meeting the Tehachapi Mountains upland with a rather definite angle, must indicate either faulting near the base of the scarp (but topographically above the basal contact line of the sediments) or a sharp warp in the bedrock. And it is probably not a coincidence that a rather bold scarp in the older rocks lies nearly in line with it on the opposite side of Tejon Creek, along the southeast side of Cummings Valley, on the block uplifted by movement along the Tejon Canyon fault. The Cummings Valley scarp is more or less continuous with the impressive escarpment along the south side of Tehachapi Valley, and the structural break along its base may be continuous with the Cache Creek reverse fault or overthrust, as will be mentioned farther on.

Structure along Mojave Desert Side of Range. It has often been held that the Tehachapi Mountains were uplifted and differentiated from the Mojave Desert block by movement on the Garlock fault, but this is true only for about the northeastern third of the range from the San Andreas fault to Jawbone Canyon. From a point near Warren, northwest of Mojave, northeastward to Jawbone Canyon, the range front is a straight, bold fault scarp 2,000 to 2,500 feet high, with the Garlock fault at its base. This break is mainly a strike-slip fault, with left-lateral displacement that has been estimated to be at least several miles.

Southwestward from Warren, the Garlock fault lies within the mountains, at average distances from their southeastern base that increase irregularly from a mile or two near Warren to 6 or 7 miles near the San Andreas fault. For nearly all of the distance from Warren to Oak Creek, the apparently normal Warren fault, subparallel to and probably a branch of the Garlock fault, defines the southeast base of the mountains, the slice between the two faults having been elevated along with the mountain mass. Southwestward from Oak Creek to the point where Tertiary strata appear along the base of the range, the physiography suggests that the front of the range is determined in part by local faults that make large angles with the Garlock fault, and in part by warping. The Garlock fault, which here lies well within the range, gives little indication of dip-slip movement, and seems to have had little or no part in uplifting the Tehachapi Mountains. In the most southwesterly 10 miles of the range front, the Tertiary and older Quaternary sediments dip in general toward the desert region, and a number of faults have been mapped by Crowell (1952) and by Fine (1947). Most of them have trends that differ considerably from that of the Garlock, and are not connected with this major break. The faults presumably had some relation to the uplift of the range, but this section of the range front apparently was determined mainly by warping.

Structure within the Range. In contrast to the rigid Sierra Nevada block, which was little deformed during Tertiary time, the Tehachapi Mountains were both strongly folded and faulted internally, and probably at several times during the Tertiary period. The Witnet formation, early Miocene or pre-Miocene in age, dips very steeply northward along Oil Canyon and gently southward along Cache Creek half a mile north of its junction with Oil Canyon, and hence apparently forms an acute syncline that trends northeast. The overlying middle or upper Miocene Kinnick and Bopesta formations likewise have been folded synclinally but less acutely so, and the broad northeast-trending fold includes several lesser folds (fig. 5) and is cut by numerous minor faults. Basic lavas, probably of Pliocene age, apparently lie unconformably on the Miocene strata. There are evidences of still other Tertiary episodes of deformation, as in the Coast Ranges to the west.

Along the southeast sides of Cache Creek and Oil Canyon, east of Monolith, the pre-Cretaceous crystalline rocks have been thrust northwestward over the pre-middle Miocene Witnet formation, which has been acutely upturned and overturned (fig. 3). This thrust, the Oil Canyon fault, dips 30° to 45° southeast. It apparently is mainly or entirely of pre-middle Miocene age, for Kinnick strata have not been found to be cut by it and patches of Kinnick, but little deformed, rest on the older rocks southeast of the fault. The surface trace of the fault is terminated northeastward by a cross fault that drops Kinnick strata down on the east side, but its alignment suggests that it may well continue in the older rocks and be responsible for Lone Tree Canyon, in which case it continues to, and is cut off by, the Garlock fault. Southwestward the Oil Canyon fault passes beneath the alluvium of Tehachapi Valley. It may terminate against an east-west fault that Lawson (1906) predicated along the south margin of Tehachapi Valley, but it appears equally probable that the Oil Canyon thrust turns somewhat westward, becomes the Tehachapi Valley fault, and is responsible for both Tehachapi and Cummings Valleys. Continuing southwestward, it would be offset by the Tejon Canyon fault, but it may well be a continuation of the zone of sharp deformation that bounds the northwest side of the Tehachapi Mountains from Tejon Canyon to Grapevine Canyon.

A second set of faults within the Tehachapi Mountains trends roughly northwest, and includes the Tejon Canyon fault, previously referred to, and the two faults that bound Bear Mountain on the northeast and southwest sides, and between which the mountain was hoisted to its present height of nearly 7,000 feet. It is not known whether these faults continue northwestward on the floor of the San Joaquin Valley beyond the White Wolf fault, or whether they terminate against it, but it is known that similar northwest-trending faults extend discontinuously northwestward beneath the valley toward structures of similar trend that plunge southeastward beneath the valley alluvium from the eastern margin of the Coast Ranges in the Coalinga area. Similar northwest-trending faults drop Tertiary formations down against the basement rocks along the eastern margin of the San Joaquin Valley east and north of Bakersfield; the great fault-line scarp at the mouth of the Kern River Gorge, 12 miles northeast of Bakersfield, is one of these. These faults are taken to be Central Coast Range structures that traverse obliquely the southern San Joaquin Valley floor and reach into the Tehachapi Mountains.

ORIGIN OF THE TEHACHAPI MOUNTAINS

The Tehachapi Mountains bear little structural or genetic relation to the Sierra Nevada, with which they merge on the northeast. They do not trend north, they do not constitute a tilted block, and the great north-trending fault zone that bounds the Sierra Nevada on the east does not reach into the Tehachapi country and has no relation to the Garlock fault, which lies along or within the south margin of the Tehachapi Mountains. On the other hand, the range trends more nearly parallel to the Transverse Ranges to the south and southwest, and it lies east of and on the projection of the structural lines of the Transverse Ranges. Instead of being a tilted block, it is a plateau or complex horst elevated between faults or sharp flexures along its San Joaquin Valley and Mojave Desert margins. It has internal structures that in nature and trend seem to be extensions of both the east-trending structures of the Transverse Ranges to the west and of the northwest-trending structures of the Central Coast Ranges projected obliquely southeastward across the San Joaquin Valley. Like the Coast Ranges, the Tehachapi Mountains experienced several mountain-making disturbances during the Tertiary period.

It is not known whether the Tehachapi Mountains ever were largely covered by Tertiary sedimentary formations similar to those in the Coast Ranges, and it is clear that some interior parts, such as that north of Monolith, were not. These parts are still underlain by some Tertiary deposits that are different from deposits of similar ages in the Coast Ranges. Typical Coast-Range Tertiary formations thousands of feet thick now dip off the margins of the Tehachapi Mountains, and plainly extended for considerable distances into the interior of the present range. In general the range apparently stood higher than the Coast Range country west of it during at least a large part of the Tertiary period, so that it was covered only in part by marine sediments and received land-laid deposits in other parts. It apparently rose much higher in late Cenozoic time, so that it is now mainly old crystalline rocks at the surface, whereas the Coast Ranges west of it still carry great thicknesses of Tertiary formations.

ORIGIN OF THE TEHACHAPI VALLEY SYSTEM

One of the remarkable features of the upland surface of the complex horst that makes the Tehachapi Mountains is the existence on it of several broad, flat-floored valleys. Lawson (1904) described the general geologic nature of these striking depressions picturesquely and accurately nearly 50 years ago. They lie at an altitude of about 4,000 feet, and hence are high above both the Mojave Desert and the San Joaquin Valley. Streams are now heading back into them from the San Joaquin Valley side, and will eventually destroy them.

The largest of these upland depressions is Tehachapi Valley, about 10 miles long and 3 miles wide, which trends east athwart the range and affords the pass for the railroad line and one of the main highways between southern and central California. To the west of it lie Brite Valley, Cummings Valley, and Bear Valley, which are smaller but otherwise similar depressions. All these valleys contain Quaternary alluvium as much as several hundred feet deep. Each of the valleys is bounded on one or more sides by a bold scarp that rises abruptly from its alluvial floor and that has been developed on old crystalline rocks. Apparently in large part because of these striking scarps, Lawson (1904) concluded that the Tehachapi valleys were formed chiefly by Quaternary faulting. The gentle southerly tilt of the upper Pliocene or Quaternary Tehachapi formation tends to support this view, although the tilt may be related to a synclinal downwarping of that formation and the underlying Cable, Tank, and Atlas formations as a separate episode, as Lawson suggested. Moreover, it is clear that Tehachapi Valley was in part eroded out of the Tehachapi formation and the Kinnick formation, as the considerable thickness of the latter unit exposed at and north of Monolith originally must have extended southward into the area now occupied by the valley and must have been removed by erosion before the thick body of alluvium was deposited on the valley floor.

The writer knows of no Tertiary strata on the south side of Tehachapi Valley or in Brite, Cummings, or Bear Valleys, and hence has no clue as to their original distribution in these valleys. The apparently necessary inference that Tehachapi Valley was at least in part formed by erosional removal of these less resistant beds, and the physiographic similarity of these other three valleys to the larger valley, leads to the supposition that they also are at least in part excavational rather than entirely tectonic in origin. No evidence of faulting so recent as to cut the alluvium has been found along any of the scarps. The northwest-trending scarps on the two sides of Bear Mountain appear to be bolder and younger than the east-trending scarps along the south side of Tehachapi, Brite, and Cummings Valleys, and it is entirely possible that the former are true fault scarps and that the latter are in part fault-line scarps resulting from the erosional excavation of Tertiary beds to form the three valleys. The excavation presumably would have occurred during or after uplift of the horst.

GEOLOGIC HISTORY OF THE TEHACHAPI MOUNTAINS

The geologic history of the Tehachapi Mountains is at best a very incomplete record of the episodes of uplift, erosion, deposition of sediments, volcanism, folding, faulting, and metamorphism, and is further limited by the small fraction of the range that has been mapped or studied in detail. Probably the earliest known event in the evolution of the range is recorded in patches of metamorphosed sediments believed to be of pre-Cambrian age. These now are mainly schist (the Pelona schist), and are present between Tehachapi and Mojave, as well as in larger areas in the southwest part of the range, where they have been described by Wiese (1950). These rocks are believed to represent mainly the fine-grained sediments laid down in one or more invasions of a pre-Cambrian sea.

Another epoch of pre-Cambrian marine deposition probably is represented by a body of rocks, termed by Wiese (1950) the ''gneiss complex,'' in the southwestern part of the range. Partly old sediments and partly intrusive rocks, this complex indicates another long chapter of pre-Cambrian history, but whether this was earlier or later than the deposition of the Pelona schist is not certain.

What occurred in this region during the early and middle parts of the Paleozoic era is not known, but probably in Carboniferous time another marine transgression resulted in deposition of a thick section of limestones, sandstones, and other sedimentary strata. Diastrophism followed in later Paleozoic or early Mesozoic time, and during or after the deformation intrusive rocks invaded the sediments. These igneous bodies were more basic in composition than the widespread granodioritic intrusives of later Mesozoic age, and commonly are now more gneissic.

There is no known record of Mesozoic sedimentation in the entire Tehachapi Mountains, but presumably during the Jurassic period widespread intrusion of batholithic rocks occurred, ranging in composition from gabbro to granite but dominantly of granodioritic type. The exact date of this igneous activity has not been determined in this region, but the similarity of the rock types to those in the Sierra Nevada farther north has led to the assumption that these intrusive formations are ''part of the granites of the Sierra Nevada.''

Presumably just preceding and during the intrusion of the granodioritic rocks in Jurassic time, vigorous mountain making affected this region as it did the northern Sierra Nevada and large parts of western Nevada and southeastern California. Although the history of the Tehachapi Mountains in post-Mesozoic time seems to have been rather independent of that of the Sierra Nevada, the tectonic affinity of these regions in Jurassic time seems to be strongly indicated by the similarity in trends of the remaining patches of Paleozoic sedimentary strata, and by the structural trends in the magnificant section of Permian strata so excellently mapped in great detail by Dibblee (1952) in the El Paso Range, the mountain mass that is adjacent to the Tehachapi Mountains on the east. Deep and presumably long-continued erosion, embracing later Jurassic, Cretaceous, and perhaps early Tertiary time, stripped away the roof rocks of these Jurassic intrusive bodies in the Tehachapi Mountains and much of the surrounding region, except for scattered patches of Paleozoic and pre-Cambrian sediments and gneissic intrusives.

What episodes of mountain making, deposition, and erosion occurred on the granitic platform of what is now the Tehachapi Mountains during Cretaceous and early Tertiary time is not known. At some date previous to middle Miocene time, and presumably during the Oligocene epoch, deformation within the range was sufficiently intense to result in deposition of angular arkosic sediments and interstratified dark shales nearly a mile thick. Well-rounded and polished cobbles among these angular, presumably land-laid sediments (Witnet formation) imply the erosional destruction of some older coarse-grained sedimentary formation in the region, as well as earlier mountain making leading to the deposition of that unknown sedimentary unit.

Presumably in later Oligocene or in early Miocene time vigorous deformation again occurred. The Witnet formation was strongly folded, and granitic rocks were thrust over it from the south along the Oil Canyon fault. Then, as far as can be determined from the limited remaining areas, erosion again reduced much of the relief that resulted from the mountain making.

In middle and upper Miocene time volcanism led to accumulation of many hundreds of feet of basic lavas and associated highly colored tuffs (Kinnick formation). This activity must have been accompanied by further crustal deformation, for resting on the volcanic rocks are some thousands of feet of land-laid, largely non-volcanic sediments (Bopesta formation) clearly derived from highlands surrounding the basin of deposition. They resulted from weathering, transportation, and deposition under semi-arid conditions. Both the Kinnick and Bopesta beds contain vertebrate fossils that demonstrate their middle or late Miocene age.

On the San Joaquin Valley side of the Tehachapi Mountains is recorded a Tertiary history of repeated uplift and depression of the mountain mass relative to sealevel or to baselevel. Near Grapevine Canyon the sea must have covered neighboring parts of the range during upper Eocene time, when the Tejon formation was deposited to a thickness of thousands of feet at its type section. Emergence was followed by the deposition of the Oligocene (?) Tecuya formation, and at about this same time the thick section of the land-laid Walker formation, with its Bealville conglomerate, was deposited farther northeast, in the Caliente Creek region (Dibblee, 1953). It is not known whether these formations were laid down earlier than, contemporaneously with, or later than the Witnet formation within the range.

Little is known about the Eocene and Oligocene history of the southeast margin of the range, as no rocks of these ages have been recognized there. However, the type section of the Rosamond formation, mainly volcanic rocks and continental beds of probable Miocene age, accumulated in the neighboring part of what is now the Mojave Desert. In upper Miocene time the sea invaded the western end of the Mojave Desert and deposited Santa Margarita beds on the southeast flanks of the western part of the Tehachapi Mountains, and this was followed by accumulation of a considerable thickness of continental beds. This is the only known record of post-Paleozoic marine deposition in the Tehachapi Mountains or adjacent parts of the Mojave Desert.

In Pliocene time a fresh-water lake received some thousands of feet of sediments along the Antelope Valley margin of the range, presumably as the result of uplift of the range and relative depression of the adjoining margin of the Mojave Desert. Farther northeast, in an area northwest of Mojave and between that area and Redrock Canyon still farther northeast, terrestrial strata (Ricardo formation) accumulated to similar thicknesses, and entombed vertebrate fossils that provide a good view of the nature of mammalian life roaming the semi-arid plains and hill country of that time.

The deposition of the continental Ricardo formation on the southeast margin of the range, and of the Chanac formation and the Kern River gravels along the northwest base of the range, doubtless resulted from further uplift and deformation within the Tehachapi Mountains in post-Miocene time. No Pliocene strata were laid down within the range, so far as is known, but the Bopesta formation was moderately folded along east-west axes, and was cut by faults. Probably, but not certainly, both it and the older formations on which it rests were bevelled off, and in later Pliocene time andesitic flows and agglomerates, of which only patches now remain, probably buried a large part of these Tertiary sediments. One remnant of the flows now caps Cache Peak, north of Tehachapi Valley, at an altitude of 6,700 feet.

In late Pliocene and Quaternary time deformation apparently continued within the range, as the Pliocene or Quaternary Tehachapi formation of the northwest corner of Tehachapi Valley was folded and tilted so that it now extends beneath the valley alluvium. If the Tehachapi valley system developed mainly by late faulting, it must have been at this time, as the marginal scarps are in part still bold. Certainly faulting within the range occurred during Quaternary time, as shown by the northeast and southwest faces of Bear Mountain. If the origin of the Tehachapi valleys was mainly erosional, they must have been excavated during Quaternary time. But the larger-scale deformation during Quaternary time was by faulting and warping along both margins of the range, and by elevation of the complex Tehachapi Mountains horst between the two fault systems. The mountain mass rose 2,000 to 3,000 feet with reference to the Mojave Desert block southeast of it, which itself may well have been elevated somewhat at this time, and the mass was lifted 5,000 feet or more with reference to the San Joaquin Valley. To judge by the seismic activity, the locally offset alluvial surfaces, and the freshness of the scarps, this marginal faulting, and presumably the marginal warping and the uplift, are still continuing. In addition, the last episode in the recent history includes the vigorous dissection and degradation initiated by the last uplift of the range.

In summary, the Tertiary history of the Tehachapi Mountains, like that of the Transverse Ranges west and southwest of them, is one of repeated deformation, subsidence, and uplift, with resultant deposition of marine or land-laid sediments and volcanic rocks in constantly shifting areas and their equally irregular erosional removal, giving rise to numerous unconformities and complex areal distribution and structural relationships. It appears that the range was in existence during most of Tertiary time, as suggested by the structural relations of the sediments along its flanks, but in general it probably stood much lower than at present. The thick Tertiary sediments, now truncated along its margins, must have covered much larger parts of the range during a considerable part of the time, and the continental sediments within the range clearly extended at times over much larger areas. Late in the Cenozoic era—so late that dissection has not yet reached into the interior of its wider parts—the range was uplifted vigorously. This resulted in rapid stripping of sediments both in the interior and along the margins, and produced a complex horst in which old pre-Cretaceous intrusive rocks are widely displayed at the surface.

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10. GEOLOGY OF THE CENTRAL AND SOUTHERN DEATH VALLEY REGION, CALIFORNIA†

By Levi F. Noble * and Lauren A. Wright **

INTRODUCTION

That the geology of the desert region bordering and including the central and southern parts of Death Valley is exceedingly complex and reflects an unusual geologic history is immediately evident from a glance at the accompanying geologic map (plate 7). Only parts of the region have been studied in detail, so that the geology is imperfectly known; but enough information is available to piece together the broad outline of the salient geologic features set forth below.

The region considered here (plate 7) is 90 miles long in a northerly direction and 57 miles wide. It is characterized by mountain ranges and valleys that for the most part trend north to northwest. The most prominent of these features are the central part of Death Valley and the mountain ranges that bound it—the Panamint Range on the west and the Funeral and Black Mountains on the east. In easterly succession from the Black Mountains lie the Furnace Creek-Greenwater Valley, the Greenwater Range, Amargosa Valley, the Resting Spring Range, Chicago Valley, and the Nopah Range. Southeast of the southern end of the Panamint Range, and separated from it by Wingate Wash, are the Owlshead Mountains which are roughly circular in plan. The east- to southeast-trending Avawatz Mountains lie at the southern end of Death Valley and are separated from the Owlshead Mountains and their westerly extension, the Quail Mountains, by Owl Spring Wash and the Leach trough. The southern part of Death Valley lies between the Owlshead and Black Mountains and is aligned more northwestward than the central part, which trends nearly north. All the topographic features noted above are rather well-defined structural elements, and will be described as such in the discussion to follow.

Published geologic maps (fig. 1) within the area of the accompanying map (plate 7) cover parts of the eastern slope of the Panamint Range (Murphy, 1932; Hopper, 1947); the central Black Mountains (Curry, Contribution 7, Chapter IV); the Virgin Spring area of the southern Black Mountains (Noble, 1941); the Leach Trough-Quail Mountains area south of the Owlshead Mountains (Muehlberger, Map Sheet No. 16, this volume); an area of saline-bearing Tertiary rocks at the north base of the Avawatz Mountains (Johnson and Lewis, in Ver Planck, 1952; Durrell, 1953); the Tecopa area (Mason, 1948); a part of the Saratoga Hills (Wright, 1952a); the Silurian Hills (Kupfer, Map Sheet No. 19, this volume); and the Alexander Hills area (Wright, Map Sheet No. 17, this volume). Unpublished maps of the Greenwater Range and of the valley of Furnace Creek from Ryan to Death Valley, together with data on the geology of these areas, have been kindly supplied by T. P. Thayer. The writers have utilized all of these sources of information, as well as an unpublished map of the central Black Mountains by H. D. Curry, and Wright's unpublished geologic map of the southern half of the Tecopa quadrangle. All of the area of the accompanying map (plate 7) has been studied in reconnaissance by the writers, but Wright's work has been confined largely to the southeastern and west-central parts.

ROCK FORMATIONS ††

Undifferentiated Earlier Pre-Cambrian Rocks. A complex composed mostly of gray granitic to dioritic gneiss, but containing subordinate quartzite, mica schist, migmatite, amphibolite, carbonate strata, and intrusive bodies of granitic rocks, is extensively exposed in the Black Mountains (fig. 3) and Ibex Hills, and also underlies smaller areas in the southeastern part of the Panamint Range, Greenwater Range, southern Nopah Range, and Alexander Hills. The earlier pre-Cambrian age of this complex is established by the existence of an unconformably overlying section of later pre-Cambrian sedimentary rocks—the Pahrump series. Metamorphic and plutonic igneous rocks, extensively exposed on the north and east slopes of the Avawatz Mountains, on the crest and south slopes of the Owlshead Mountains near Owl Hole Springs, and in the northwestern part of the Funeral Mountains, are probably also earlier pre-Cambrian in age. In the Avawatz Mountains they consist mostly of quartz diorite and quartz diorite gneiss that contains xenoliths of marble; in the Owlshead Mountains they include marble, quartzite, and quartz diorite; and in the Funeral Mountains they include phyllite, schist, marble, quartzite, and quartz diorite gneiss.

Later Pre-Cambrian Rocks. Unmetamorphosed sedimentary rocks and diabase that comprise the later pre-Cambrian Pahrump series crop out at many places in a belt extending from Galena Canyon in the southeastern part of the Panamint Range southeastward for 75 miles to and beyond the Kingston Range at the east margin of the map area (plate 7). Recent studies suggest that metamorphic rocks probably correlative with the Pahrump series form most of the crest and west slopes of the Panamint Range beyond the west border

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† Publication authorized by the Director, U. S. Geological Survey.
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†† Not all formation names used in this paper have been recognized by the Geological Survey.

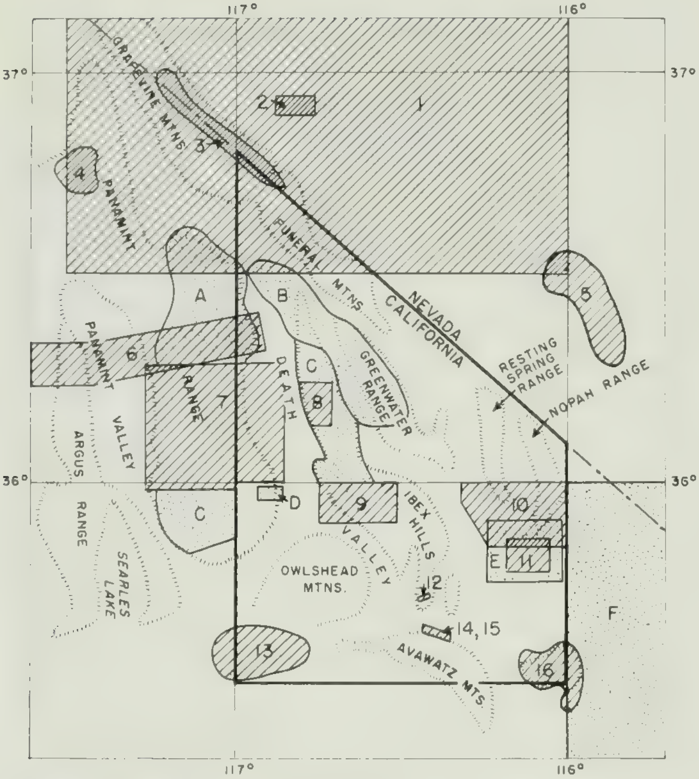

FIGURE 1. Index map of the Death Valley region showing area of plate 7 enclosed in heavy line and areas covered by other maps, published (shaded) and unpublished (dotted). As numbered, the published maps are by the following workers: 1. Ball (1907), 2. Ransome, Emmons, and Garrey (1910), 3. Stock and Bode (1935), 4. McAllister (1952), 5. Nolan (1929), 6. Hopper (1947), 7. Murphy (1932), 8. Curry (1954), 9. Noble (1941), 10. Mason (1948), 11. Wright (1954), 12. Wright (1952a), 13. Muehlberger (1954), 14. Johnson and Lewis in Ver Planck (1952), 15. Durrell (1953), and 16. Kupfer (1954). As lettered, the unpublished maps are by the following workers (A) D. H. Sears, (B) T. P. Thayer, (C) H. D. Curry, (D) L. A. Wright, (E) L. A. Wright, and (F) D. F. Hewett.

of the map area (B. K. Johnson, personal communication, 1954; D. H. Sears, personal communication, 1954).

Throughout the 75-mile belt of unmetamorphosed Pahrump strata, the series is divisible into three formations described by Hewett (1940) in the Kingston Range east of the border of the map (plate 7). The lowest and most extensively exposed is the Crystal Spring formation, which is commonly about 4,000 feet thick and consists mostly of various clastic sedimentary rocks and diabase (Wright, 1949; 1952a). A carbonate member, several hundred feet thick, generally occurs near the middle of the formation and locally has been altered to deposits of commercial talc. This formation is successively overlain by the Beck Spring dolomite, about 1,000 feet thick, and the Kingston Peak formation, which consists mainly of quartzite and conglomeratic quartzite and which probably is several thousand feet in maximum thickness. The Kingston Peak formation contains abundant detritus from both of the lower Pahrump formations, but the unconformity thus indicated has not been detected by mapping.

Cambrian Rocks. In the southern and central Death Valley region, the strata that have been assigned a Cambrian age total about 17,000 feet in thickness and comprise more than three-quarters of the exposures of Paleozoic rocks. The Cambrian section of the Nopah and Resting Spring Ranges has been measured and mapped in greatest detail (Hazzard, 1937; Mason, 1948; Wright, Map Sheet No. 17, this volume). It comprises, from bottom to top, about 1,000 feet of massive Lower Cambrian dolomite (Noonday dolomite), an additional 8,000 feet of Lower Cambrian strata that consist mostly of quartzite and shale (Johnnie formation, Stirling quartzite, and Wood Canyon formation), 5,300 feet of Middle Cambrian dolomite (Cadiz, Bonanza King, and Cornfield Springs formations), and 1,700 feet of Upper Cambrian dolomite (Nopah formation).

The lowest beds that contain diagnostic fossils are high in the Wood Canyon formation, and the fossils are Lower Cambrian. The underlying units, including the Noonday dolomite, apparently are conformable with the Wood Canyon, but no fossils other than algal(?) remains have been recognized in them. Because the Noonday dolomite is separated from the Pahrump series by a widespread angular unconformity, Hazzard (1937) placed the base of the Cambrian at this contact. A marked lithologic change, however, occurs at the base of the Stirling quartzite. The underlying Johnnie formation and Noonday dolomite are lithologically more similar to the rocks of the Pahrump series than to rocks in the overlying Paleozoic formations, show vertical variations in lithology and color that are much more abrupt than variations in the Stirling quartzite and higher formations, and contain algal(?) beds of a type different from those in the higher formations.

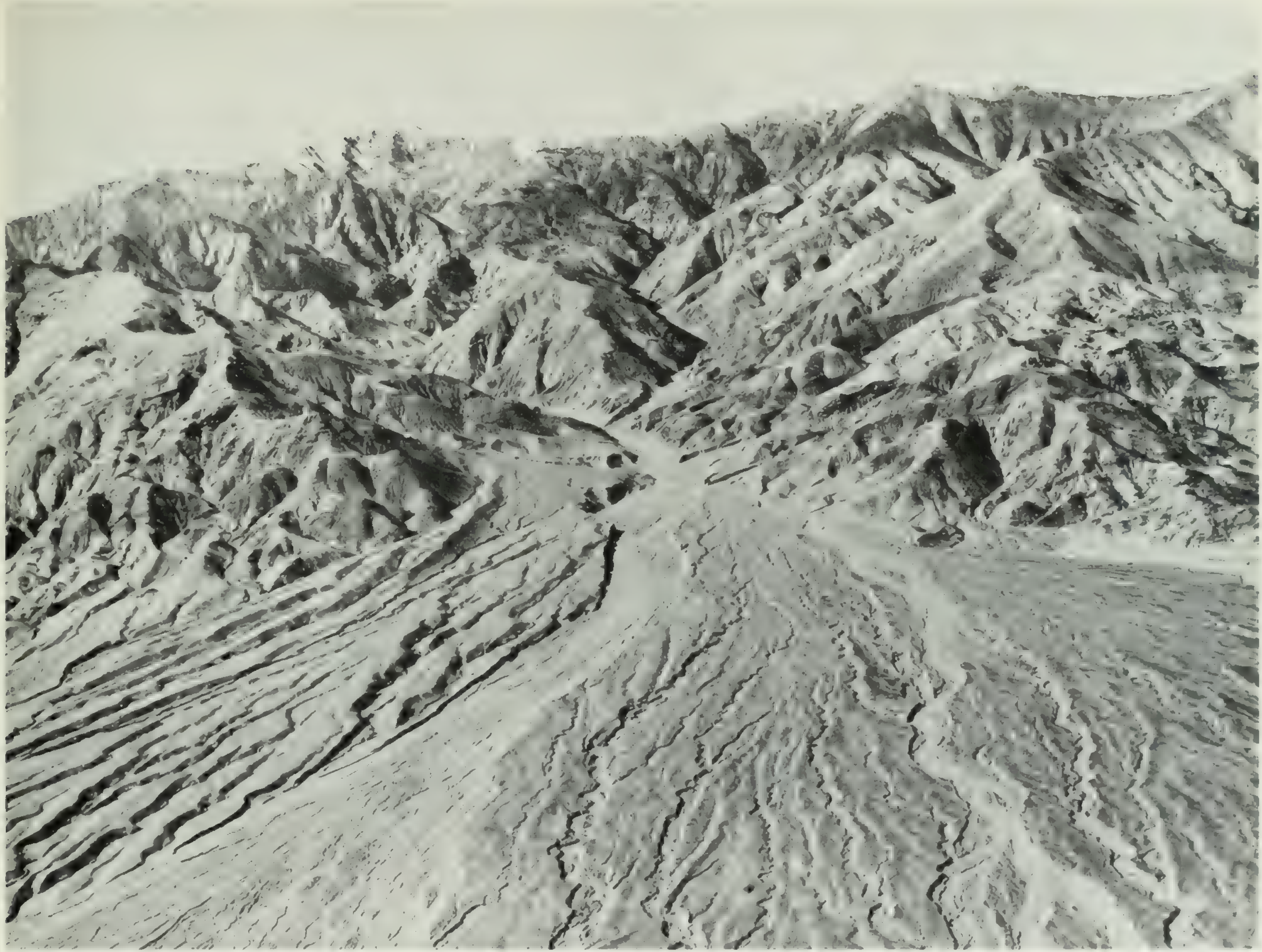

FIGURE 2. View westward at east face of Panamint Range, showing Hanaupah Canyon and Telescope Peak (left skyline). The mountain slopes are underlain by Cambrian strata that dip toward viewer. Note size and dissection of Hanaupah fan. Gully dissection of upper part of fan has a relief of about 200 feet. Compare with alluvial fans along Black Mountains on opposite side of valley (fig. 3). *Spence Air Photos.*

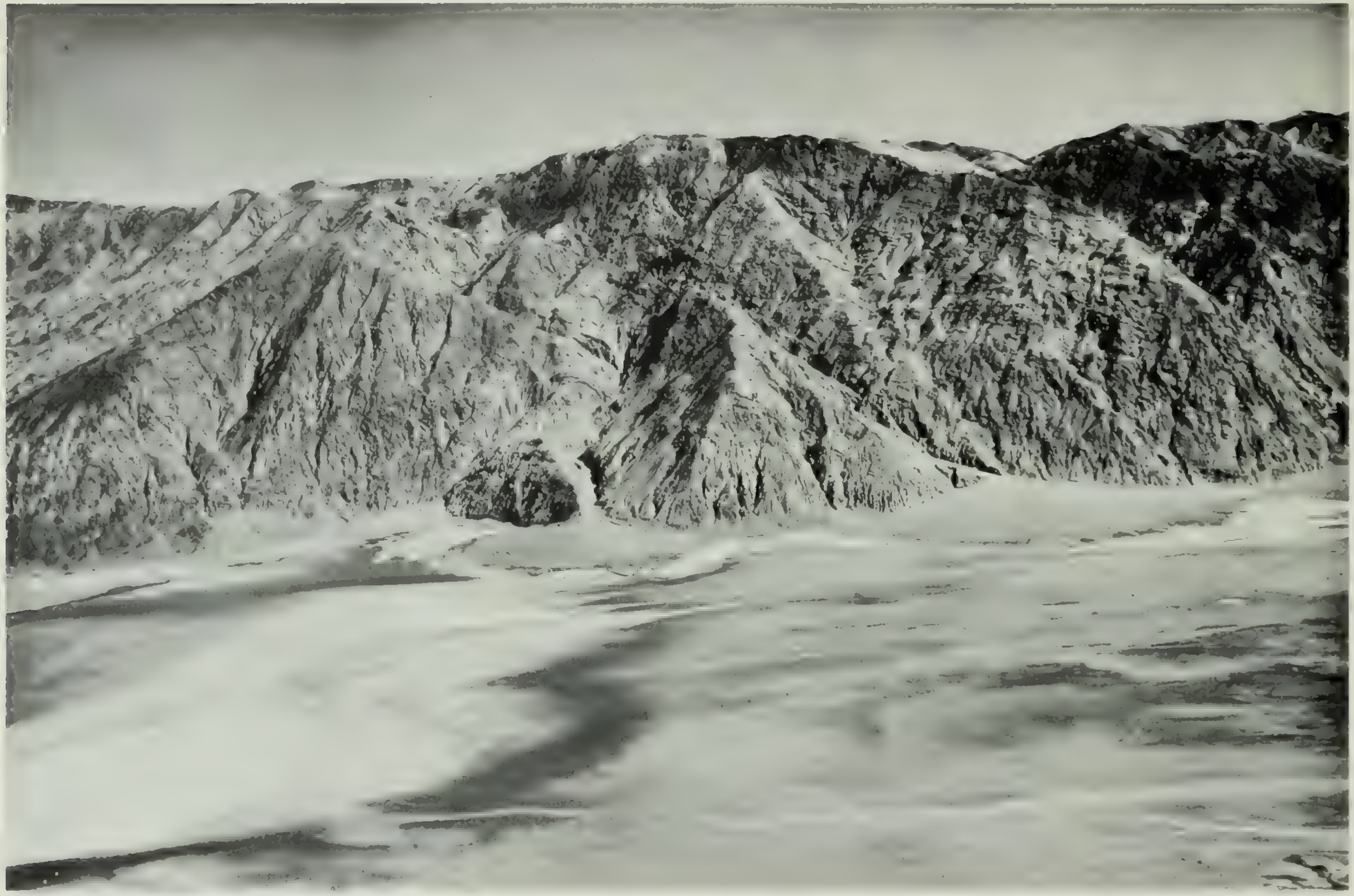

FIGURE 3. View eastward at west face of Black Mountains, showing Dantes View on center skyline and Badwater at left of alluvial fan in center of photo. Mountain front consists essentially of earlier pre-Cambrian metamorphic rocks capped by Tertiary volcanic rocks. Relatively dark spur at extreme left of view is surface of north-plunging Badwater turtleback. Floor of Death Valley is rock salt. Note small size and lack of dissection of alluvial fans compared with Hanaupah Canyon fan (fig. 2) on opposite side of valley. *Spence Air Photos.*

The Cambrian rocks of the Panamint Range (Murphy, 1932; Hopper, 1947) and Funeral Mountains, although less well known, appear comparable in thickness with those of the Resting Spring and Nopah Ranges, and consist of essentially the same formations. Most of the rocks designated by Murphy (1932) as the Telescope group are now correlated with the Noonday dolomite and Johnnie formation (D. H. Sears, personal communication, 1954).

Post-Cambrian Paleozoic Rocks. Paleozoic sedimentary rocks of post-Cambrian age occur in relatively intact sections on the northeast flank of the Nopah Range, the southern part of the Funeral Range, and the east flank of the Panamint Range north of Death Valley Canyon. In addition, Permian strata form a wedge enclosed by granite in the Warm Springs Canyon area, in the southeastern Panamint Range.

In the Nopah Range the post-Cambrian Paleozoic section is nearly 7,000 feet thick (Hazzard, 1937; 1951), and all formations, except the Middle Ordovician Eureka quartzite, consist mostly of carbonate strata. The Lower and Upper Ordovician and Silurian rocks are mostly dolomite; the Mississippian and Pennsylvanian rocks are predominantly limestone. The post-Cambrian Paleozoic sections in the Panamint Range and Funeral Mountains are similar in lithology to the one in the Nopah Range, but have not been described in detail. The Panamint Range section probably is thicker than the other two, because it contains the additional Permian unit in Warm Springs Canyon that is at least 4,000 feet thick (C. T. Wrucke, personal communication, 1954).

Mesozoic Rocks. Although Mesozoic rocks have not been positively identified in the mapped area, the granitic intrusive rocks described below are probably for the most part Mesozoic in age. Volcanic and fossiliferous sedimentary rocks of Triassic age (B. K. Johnson, personal communication, 1954) are present in Butte Valley, which is in the southern Panamint Range just west of Warm Springs Canyon and just outside the area of the accompanying map. It is possible that Mesozoic volcanic rocks underlie other parts of the Death Valley region and have been mapped with the older Tertiary rocks.

Granitic Intrusive Rocks. Granitic intrusive rocks, whose age and variations in composition are not fully known, are widespread in the Death Valley region. Much the largest body of granite underlies the Owlshead Mountains, and smaller bodies are exposed in the Black, Greenwater, Avawatz, Granite, and southern Panamint Ranges. Most of the granite approximates quartz monzonite in composition. In some areas it is uniformly coarse grained, but in others it is porphyritic or shows a wide variation in texture.

Some granite that intrudes the earlier pre-Cambrian metamorphic complex is pre-Cambrian, as it is truncated by basal beds of the Pahrump series. This granite is not shown on the map. Most of the granite that is shown on the map was intruded in Mesozoic time and is genetically related to similar granite abundant in the desert region of eastern California, as well as in the southern California and Sierra Nevada batholiths. A Mesozoic age is suggested for the granite in Warm Springs Canyon, at the southern end of the Panamint Range, as it does not intrude Tertiary volcanic rocks, but does cut all older rocks including those of Triassic age in Butte Valley, just west of the area mapped.

Some of the granite in the Death Valley region may be Tertiary. Thayer (cited by Noble, 1941, p. 954) has noted that, in the Black Mountains and Greenwater Range, porphyritic granitic rock cuts volcanic rocks that appear to be part of the Artist Drive formation. In an area near the Amargosa River, southwest of the Alexander Hills, porphyritic granite contains xenoliths of volcanic rock whose age is unknown but may be Triassic.

Tertiary Rocks. Volcanic and sedimentary rocks of Tertiary age are widespread in the southern and central parts of the Death Valley region. They underlie Death Valley and all the other large topographic depressions, and lie irregularly upon the slopes and crests of the mountain ranges. In general, the sedimentary rocks (clay shales, siltstones, sandstones, and conglomerates) occupy the depressions, which appear to have existed in Tertiary time as troughs and basins of deposition. At many places the volcanic and sedimentary rocks interfinger.

Within the area of plate 7, Tertiary strata have been dated by fossils at only two localities, and the dating is not precise. Leaves found in the Furnace Creek formation in lower Furnace Creek Wash are believed to be early Pliocene in age (Axelrod, 1940). In the Copper Canyon area, on the west slope of the central part of the Black Mountains, beds that are lithologically similar to the Furnace Creek formation contain animal footprints that indicate an age somewhere between late Miocene and middle Pliocene (Curry, 1941).

In the bordering areas the evidence for dating Tertiary formations likewise is scanty. The oldest Tertiary strata yet recognized in the general region occur on the north side of the Grapevine Range near the head of Titus Canyon, north of the area of plate 7. These have yielded Oligocene Titanothere remains (Stock and Bode, 1935, pp. 573-579), and are part of the Titus Canyon formation (Stock and Bode, 1935). Tertiary strata on the south slope of the Avawatz Range, 10 miles south of the area of plate 7, have yielded a mammalian fauna identified by Henshaw (1939) as upper Miocene(?) or lower Pliocene(?) in age.

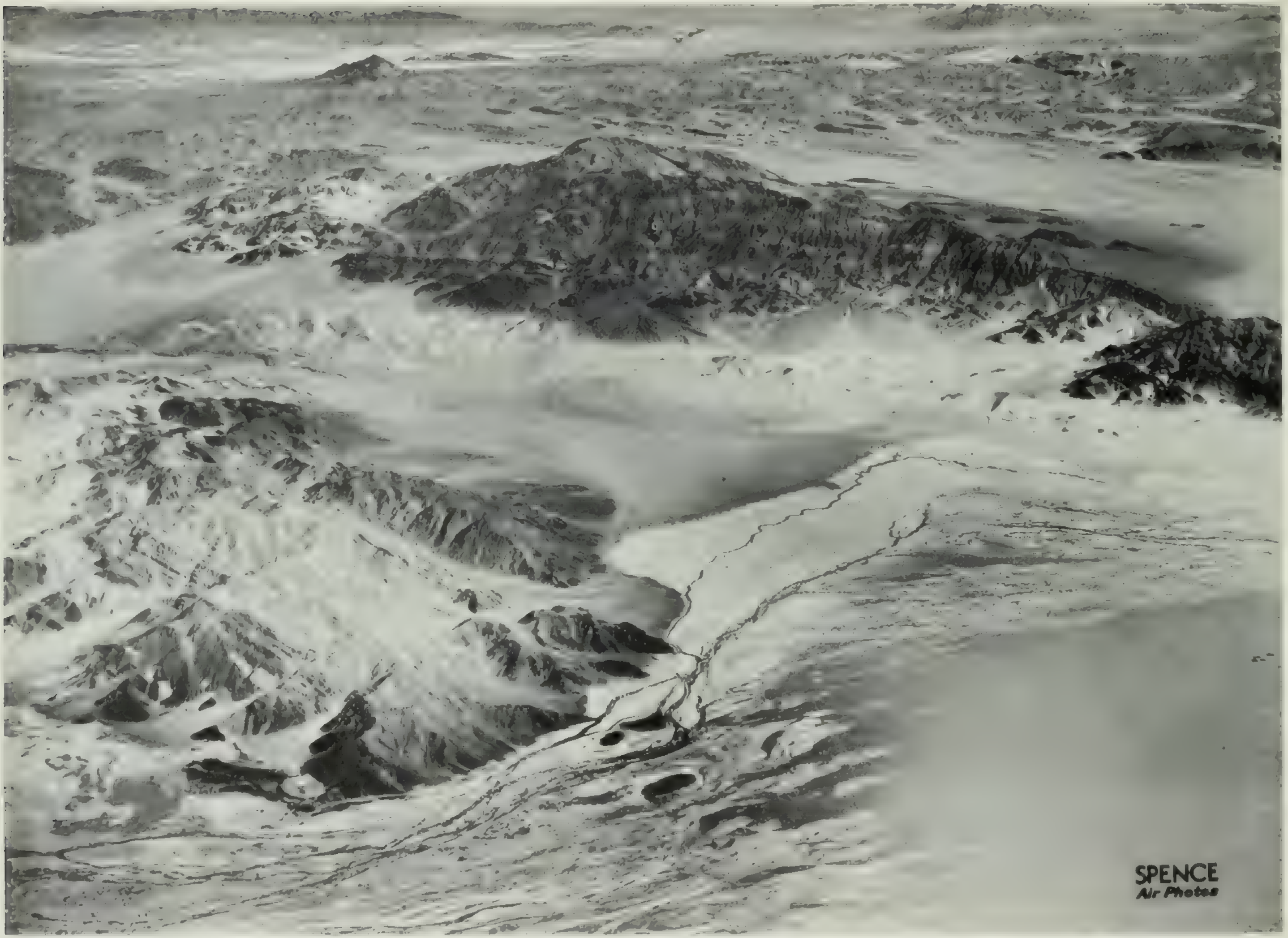

FIGURE 4. View northeastward across Saratoga Hills (left foreground) and Saddle Peak Hills (center), east of South Death Valley. These hills are east-tilted fault blocks, each consisting mostly of later pre-Cambrian strata of the Pahrump series. Highest part of Saddle Peak Hills is capped by lighter-colored Noonday dolomite of Lower Cambrian age. Amargosa River is on floor of South Death Valley in foreground. *Spence Air Photos.*

The most complete section of Tertiary rocks in the Death Valley region is in the northern part of the Black Mountains (figs. 5 and 6). Thayer (cited in Noble, 1941, p. 955) has estimated that this section is about 13,000 feet thick. Its lowest part probably is correlative with the Oligocene Titus Canyon formation (Stock and Bode, 1935); its higher part, consisting of Miocene and Pliocene rocks, is overlain unconformably by beds of the Pliocene-Pleistocene(?) Funeral fanglomerate. On the accompanying map (pl. 7) most of the Tertiary rocks have been grouped into the two subdivisions described below.

Included in the older Tertiary rocks are the Titus Canyon formation (Stock and Bode, 1935) and the Artist Drive formation. The Titus Canyon formation lies upon the north slopes of the Grapevine and Funeral Mountains in a narrow belt that extends into the mapped area to a point north of Chloride Cliff in the northern part of the Funeral Mountains, where it is about 1,300 feet thick and consists mostly of conglomerate, sandstone, and mudstone (Stock and Bode, 1935, p. 574). Isolated patches of similar rocks lie in and near Boundary Canyon at the north end of the Funeral Mountains and on the southern tip of the Funeral Mountains west of Death Valley Junction. A small patch lies on the south tip of Eagle Mountain, south of Death Valley Junction.

In the Black Mountains the Artist Drive formation, which is probably Oligocene in the lower part and Miocene in the upper part, has an estimated thickness of more than 5,000 feet (Thayer, cited by Noble, 1941, p. 955), and consists mostly of alternating basaltic and latitic flows, tuffs, and breccias interlayered with various sedimentary rocks. Other older Tertiary volcanic and sedimentary rocks, which appear to be at least partly correlative with the Artist Drive formation, occur in the central Black Mountains and Greenwater Range. They probably also are present as local unmapped masses in the Virgin Spring area farther south, and in a belt along the northeast base of the Avawatz Mountains.

Included in the younger Tertiary rocks are the Furnace Creek formation and the Greenwater volcanics. In the northern part of the Black Mountains the Artist Drive formation is unconformably overlain by the Furnace Creek formation (Thayer, cited by Noble, 1941, p. 956), which contains fossil leaves of probable early Pliocene age. Here the Furnace Creek formation is about 2,500 feet thick and consists mostly of volcanic rocks interbedded with fanglomerate and playa sediments that contain gypsum and borates. The lower or middle Pliocene fossil footprints in the Copper Canyon area of the central Black Mountains occur in a 3,000-foot section of folded playa beds that are similar lithologically to those of the Furnace Creek formation in the northern part of the Black Mountains and in Furnace Creek Wash.

Intensely deformed Tertiary strata, several thousand feet thick, are discontinuously exposed in southern Death Valley from the north margin of the Avawatz Mountains (fig. 8) northwestward to the Confidence Hills (fig. 7). Although to date they have proved unfossiliferous, they resemble the playa deposits of the Furnace Creek formation and are assigned tentatively to that formation. They consist mostly of poorly consolidated mudstone and siltstone, and contain deposits of rock salt, gypsum, and celestite.

Volcanic rocks that are mostly acidic to intermediate in composition, and that contain little or no interlayered sedimentary rocks, are younger than the Furnace Creek formation and are 3,000 feet or more thick. In the Greenwater Range, these volcanic rocks crop out extensively. They are unconformable upon the Furnace Creek formation, and have been named the Greenwater volcanics and assigned a Pliocene(?) age (Thayer, cited by Noble, 1941, p. 955). Rocks of similar composition and stratigraphic position occur throughout the Black Mountains, and also are abundant at the south end of the Panamint Range north of Wingate Wash and on the northwest flank of the Owlshead Mountains south of Wingate Wash.

Pliocene-Pleistocene(?) Rocks. The Funeral fanglomerate, which probably is Pliocene in age, is widespread in the area mapped. At most places it consists of fanglomerate commonly interbedded with conspicuous black basalt flows and finer-grained sedimentary rocks. It rests unconformably upon all the older formations and, in general, is much less deformed (figs. 7 and 8; plate 8). At most places the formation is more than 1,000 feet thick. In the Virgin Spring area, the basal part of the formation contains layers of megabreccia.

South of Tecopa, the southern end of Amargosa Valley is marked by a broad, west-trending belt of low hills, underlain by beds that are tentatively correlated with the Funeral fanglomerate. These beds, which were named the China Ranch beds by Mason (1948), are moderately deformed (plate 8) and are flanked on the north and unconformably overlain by conglomeratic lake beds of Pleistocene age. The China Ranch beds are 5,000 or more feet thick and consist mostly of fanglomerate and siltstone (Wright, Map Sheet No. 17). They contain lenses and layers of megabreccia composed mostly of granitic and volcanic rocks and later pre-Cambrian and Cambrian sedimentary rocks. These megabreccias formerly were interpreted as thrust slices (Noble, 1941, p. 992), but most of them are now thought to be breccias of debris-flow origin formed down-slope from large faults and comparable to the megabreccias described by Longwell (1951, pp. 343-355).

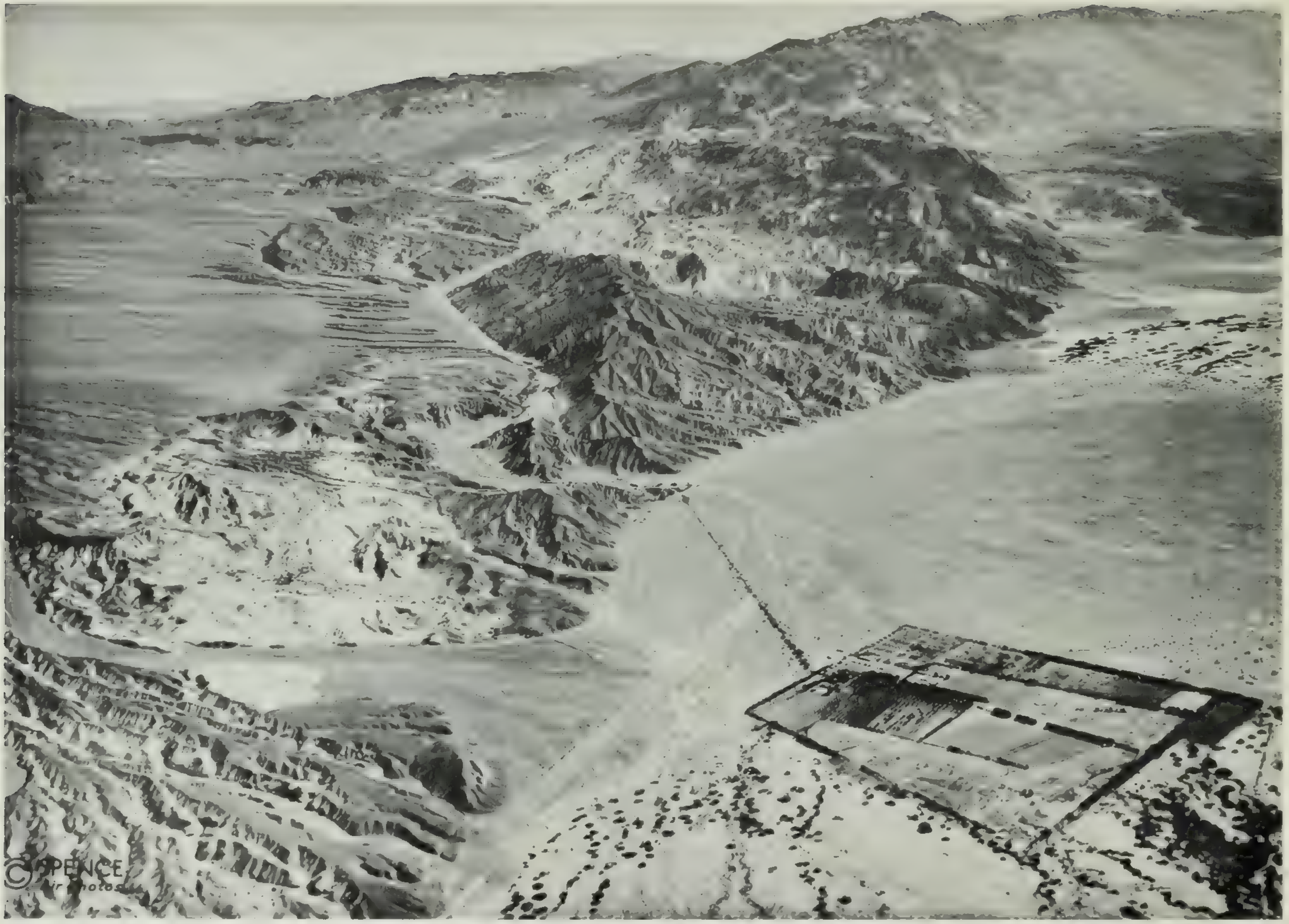

FIGURE 5. View southeastward along east edge of Death Valley, looking up Furnace Creek Wash (center of photo). Furnace Creek Ranch is the rectangle in right foreground; Furnace Creek Inn is at mouth of wash; Black Mountains are at right of wash. This part of the Black Mountains consists of complexly folded and faulted Tertiary sedimentary and volcanic rocks, which in general dip northeast toward Furnace Creek Wash and are overlain by the Pliocene-Pleistocene(?) Funeral fanglomerate. Curved base of Black Mountain front marks the trace of Artist Drive fault. Light-colored rocks south of Furnace Creek Wash are borate-bearing beds of younger Tertiary Furnace Creek formation exposed in south limb of Furnace Creek syncline, whose axis trends northeast and lies beneath Quaternary alluvium on left of Furnace Creek Wash. *Spence Air Photos.*

Quaternary Rocks. Quaternary rocks, which are unconformable upon the Funeral fanglomerate and all older rocks, include alluvial fans, playa and lake deposits, sand dunes, and local occurrences of basaltic cinders and cinder cones. Salt, interlayered with clay, underlies at least 125 square miles of the floor of Death Valley (fig. 3 and plate 8); several holes, drilled to depths of 600 to 1,000 feet, did not penetrate its base.

TOPOGRAPHIC AND STRUCTURAL ELEMENTS

Southern Panamint Range. Although the internal structure of the southern Panamint Range is complex, the range is essentially an east-tilted fault block, bounded on the west in Panamint Valley by a major zone of normal and strike-slip faulting. Its eastern, or Death Valley face (fig. 2), partly shown on the accompanying map, consists mainly of east-dipping Paleozoic formations (see cross section, plate 8). Earlier pre-Cambrian and later pre-Cambrian (Pahrump ?) metamorphic rocks compose much of the west face of the range, beyond the margin of the map (Murphy, 1932; Hopper, 1947; B. K. Johnson, personal communication, 1954; D. H. Sears, personal communication, 1954). Triassic rocks have been recognized only in the southern part of the range, west of the mapped area. East-dipping Tertiary rocks lie upon lower spurs of the range along the margin of Death Valley, but they do not occur in the high central part of the range. Bodies of granitic rocks intrude all except the Tertiary rocks.

The structure of all the Death Valley slope of the Panamint Range is imperfectly known. A mass of unmetamorphosed later pre-Cambrian (Pahrump) rocks is well exposed from Galena Canyon southward to Anvil Spring Canyon. These strata rest unconformably on older pre-Cambrian metamorphic rocks that are exposed in two windows, one in Warm Spring Canyon and the other in Galena Canyon. Numerous masses of Noonday (Lower Cambrian) dolomite rest on the Pahrump series, and post-Triassic granite cuts the Pahrump series and Paleozoic rocks in Anvil Spring Canyon. Many northwest-trending faults cut the strata of the Pahrump series. Some of them are recurrent and offset Tertiary rocks to a lesser degree. Some pre-Tertiary faults trend northeast.

North of Galena Canyon, except for the occurrence of intrusive granitic rocks near Telescope Peak just west of the map area and of Tertiary rocks on the lower spurs, the Death Valley slope is underlain entirely by Paleozoic rocks. These rocks are faulted and folded, and at some places they stand vertical, but they nearly everywhere dip eastward toward Death Valley (plate 8). Because they strike more northwestward than the trend of the mountain front, successively younger Paleozoic formations crop out northward at the valley border. For example, the rocks at the mouth of Six Spring Canyon are the Johnnie formation; at Johnson Canyon they are the Stirling quartzite and Wood Canyon formation; north of Death Valley Canyon, Ordovician, Silurian, Devonian, and Carboniferous strata successively extend to the valley border; and the spur at Poison Spring, at the north end of the map area, is underlain by fossiliferous Permian strata.

The younger Tertiary rocks and those of the overlying Funeral fanglomerate that occur low on the spurs dip less steeply than the underlying Paleozoic rocks, and apparently they are overlain by Quaternary salt and alluvium throughout Death Valley (plate 8). They appear to be correlative with the younger Tertiary rocks and the Pliocene-Pleistocene(?) Funeral fanglomerate that cap the Black Mountains east of Death Valley. The easterly dip of the Funeral on the spurs along the Panamint front indicates that much of the tilting occurred in Pleistocene time.

Black Mountains and Greenwater Range. The Black Mountains and the Greenwater Range, together with their southern extensions—the Ibex, Saratoga, Saddle Peak, Salt Springs, and Dublin Hills—appear to form a structural unit bounded by Death Valley on the west and south and by Amargosa Valley and the lower part of Furnace Creek Wash on the east and north. In plan this unit is lozenge-shaped, and will be designated the Black Mountain wedge. It constitutes a huge fault block, about 80 miles in length and 25 miles in maximum width, that has been squeezed between the Death Valley and Furnace Creek fault zones in such a way as to produce folding and thrusting of a peculiar type.

In its general geological features the Black Mountain wedge differs markedly from the ranges that border it. It is underlain mostly by pre-Cambrian and Tertiary rocks, contains Paleozoic rocks in relatively small volume and for the most part in great disorder, and shows large folds of the pre-Cambrian basement rocks associated with low-angle faults as the most prominent features of its internal structure. In contrast, most of the bordering (Panamint, Funeral, Resting Spring, and Nopah) ranges consist largely to almost wholly of Paleozoic rocks that are much less disordered than those in the Black Mountain wedge, contain few Tertiary rocks, and are essentially east-tilted fault blocks.

Because the Paleozoic sections that occur on both sides of the Black Mountain wedge are similar in both thickness and lithology and indicate deposition on an essentially flat sea bottom, a comparable Paleozoic section, 25,000 to 30,000 feet thick, must once have overlain the entire area of the wedge. An additional 10,000 to 15,000 feet of strata, as represented by the later pre-Cambrian rocks in the southern part of the wedge and in the Panamint Range, and by the marine and metavolcanic Triassic rocks of the Panamint Range, also may once have overlain most or all of the wedge. The missing strata indicate that a thickness of at least 25,000 feet and perhaps as much as 45,000 feet was eroded from the northern part of the wedge in the Mesozoic to early Tertiary interval as the wedge was raised along the Death Valley and Furnace Creek fault zones.

North of a line drawn through Jubilee and Sheephead Passes, the core of the Black Mountains consists of earlier pre-Cambrian gneiss and intrusive rocks. This core is discontinuously flanked and locally capped by structurally complex rock masses composed of blocks that range in age from earlier pre-Cambrian to late Tertiary. The surface of the core, against which the masses lie, is relatively smooth and has the form of large, broad folds that trend northwestward at acute angles with the north-northwest trend of the range. This surface, large parts of which have been exhumed by erosion, marks the floor of a flat thrust fault that has caused a plate of disordered blocks to override an autochthonous block that now forms the core of the range. Subsequent arching of the autochthonous block and an extensive erosional stripping of most of the plate are assumed to have produced the present surface features. These features have been studied in two adjacent areas, the Virgin Spring area (Noble, 1941) and the central Black Mountains, farther north (Curry, 1938; 1941; Contribution 7, Chapter IV).

In the Virgin Spring area the fault is a nearly continuous tectonic break that is much greater than any other break observed in the rocks above the autochthonous block. This fault, which has been named the Amargosa thrust fault (Noble, 1941, p. 961), is conceivably a feature that extends beyond the limits of the Black Mountain wedge (Noble, 1941, p. 995); but it now seems likely that it was produced by the squeezing and arching of the Black Mountain wedge under intense compression.

Most of the rocks that lie above the autochthonous block have such a disordered appearance that the term "chaos" has been applied to them (Noble, 1941, p. 964). Three phases of the chaos were recognized by Noble. The Virgin Spring phase, which everywhere rests directly on the autochthonous block, consists almost entirely of blocks whose stratigraphic range is later pre-Cambrian to Middle Cambrian, inclusive. Most of the blocks are elongate and are 200 to 600 feet long, but some are as much as half a mile long. Each block is bounded by fault surfaces and is minutely brecciated, but the original layering in most of the blocks, except those of later pre-Cambrian diabase, is discernable. The blocks commonly lie as imbricate, east-dipping slabs, crudely arranged in their normal stratigraphic succession, to form a sheet that averages about 600 feet thick. However, some adjacent blocks are derived from widely different stratigraphic horizons.

Resting on the Virgin Spring phase of the chaos are the Calico and Jubilee phases. The Calico phase is a mosaic of fault blocks composed entirely of brilliantly colored Tertiary volcanic rocks. Many high-angle faults that cut it do not cut the rocks of the autochthonous block on which it and the Virgin Spring phase rest. At some places the Virgin Spring and Calico phases appear to be separated by an unconformity of erosion, but at most places by a surface on which there has been movement. It seems probable that the movement of the Calico phase was independent of, and less than, the movement of the Virgin Spring phase and that it was separate from, though related to, the movement on the Amargosa thrust. The date of the thrusting of the Calico phase is assumed to be post-Miocene, for the rocks of this phase are those of the younger Tertiary group.

The Jubilee phase, which overlies both the Virgin Spring and Calico phases, is in part a mosaic of huge irregular fault blocks of brecciated granite and of volcanic and sedimentary rocks of Tertiary age, and in part a series of sedimentary rocks (chiefly fanglomerate) interlayered with megabreccia composed of nearly every type of rock found in the Black Mountains. Many breccia layers are formed of one type of rock. The megabreccia layers that are interbedded with the sedimentary rocks were originally interpreted as thrust slices by Noble (1941, p. 974), but he now believes that they may in part represent debris-flow accumulations developed down-slope from large faults, like the megabreccias in southern Nevada described by Longwell (1951). He believes, however, that the assemblage of huge blocks of brecciated granite and Tertiary rocks at the base of the Jubilee phase north of Ashford Mill (Noble, 1941, p. 975) represents material derived from an advancing thrust sheet. Apparently the Jubilee phase of chaos locally constitutes a basal part of the Pliocene-Pleistocene(?) Funeral fanglomerate and passes upward into the Funeral through a series of interlayered megabreccia and fanglomerate beds.

The Amargosa thrust extends northward into the central Black Mountains, where highly disordered Tertiary sedimentary and volcanic rocks rest with fault contact against the smooth surface of the autochthonous block (Curry, Contribution 7, Chapter IV). Curry has noted that the anticlinal parts of this surface resemble the carapaces of turtles and has named them "turtlebacks." He has named the three most prominent of these features, from north to south, the Badwater (fig. 3), Copper Canyon, and Mormon Point turtlebacks. The Badwater and Copper Canyon turtlebacks plunge northwestward. The Mormon Point turtleback extends southeastward into the Virgin Spring area, where it is known as the Desert Hound anticline of that area. This anticline, by far the largest of the three, is about 13 miles long and plunges at both ends. Curry states that the entire surface of the autochthonous block of the central Black Mountains marks the position of a single thrust fault, the "turtleback fault," and he suggests that this fault is an extension of the Amargosa thrust.

South of a line drawn through Jubilee and Sheephead Passes, north-trending normal faults split the Black Mountains into four east-dipping, monoclinal fault blocks (fig. 4). These faults are cut off beneath Quaternary alluvium by the Death Valley fault zone, described below. From west to east successively younger rocks are exposed in these fault blocks. The most westerly block (Talc Ridge) is composed partly of earlier pre-Cambrian gneiss and partly of the Crystal Spring formation. The most easterly block (Salt Spring Hills) is underlain by Lower Cambrian strata and intrusive granite. In the southern part of Talc Ridge and the southern part of the Ibex Hills the later pre-Cambrian Pahrump series rests with depositional contact upon earlier pre-Cambrian gneiss. Here both Pahrump and earlier pre-Cambrian rocks are part of the autochthonous block. In the northern part of Talc Ridge and the Ibex Hills, however, the Amargosa thrust cuts across the autochthonous Pahrump and earlier pre-Cambrian rocks.

The Greenwater Range is bounded on the east by the alluviated Amargosa Valley, and is separated from the Black Mountains to the west by the continuous Furnace Creek-Greenwater Valley. The range is underlain mostly by volcanic rocks of Tertiary age. These include both older and younger Tertiary volcanic rocks, as well as basalt flows of the Funeral fanglomerate. At the south end of the range the rocks rest with depositional contact upon earlier pre-Cambrian gneiss.

The base of the Tertiary section is not exposed at the northern end of the Greenwater Range. Here steeply upturned and faulted Tertiary rocks, chiefly borate-bearing beds of the younger Tertiary Furnace Creek formation, are overlain unconformably by flat-lying basalt of the Funeral fanglomerate. At Ryan, the odd pink and green colors of the Tertiary rocks beneath the contrasting black of the basalt cap are striking scenic features. South of Ryan, the younger Tertiary rocks beneath the Funeral fanglomerate consist chiefly of the Greenwater volcanics, which at Greenwater Canyon (Thayer, cited by Noble, 1941, p. 956) are unconformable upon the Furnace Creek formation.

Basalt of the Funeral fanglomerate caps the older rocks at many places in the range. Its attitudes show that the range has been folded into a broad anticline since the Funeral was deposited, and that smaller folds are superimposed on the anticline. The Greenwater Range is traversed by a system of northeast-trending faults that neither cut the Funeral fanglomerate nor extend across the bordering Greenwater-Furnace Creek and Amargosa Valleys.

The Furnace Creek-Greenwater Valley is an alluvium-filled trough that extends southwestward from the Furnace Creek Ranch in Death Valley to the Amargosa Valley. The trough drains in opposite directions from an alluvial divide at 4,000 feet near Greenwater, Furnace Creek Valley draining northwest to Death Valley, and Greenwater Valley draining southeast to Amargosa Valley. Patches of basalt of the Funeral fanglomerate, discontinuously distributed along both sides of Greenwater Valley, dip toward its center and suggest that the trough coincides with a syncline that is probably modified by faults concealed beneath the alluvium.

Furnace Creek Valley below Ryan is excavated for the most part in complexly folded and faulted beds of the Furnace Creek formation which in general dip northeast off the Black Mountains toward the axis of the valley. Along the north side of the valley (fig. 6), the formation is in fault contact with Paleozoic rocks that underlie the south end of the Funeral Mountains. This contact marks the north edge of the northwest-trending Furnace Creek fault zone that forms the northern and eastern boundaries of the Black Mountain wedge.

The Furnace Creek fault zone is poorly exposed and the details of structure are unknown, but it is believed to be a major line of dislocation that has been recurrently active since late Mesozoic or early Tertiary time, with reversals of apparent vertical movement. Horizontal striae on vertical fault surfaces west of Echo Canyon suggest that it may have had a large horizontal as well as vertical component. The earliest movements raised the Black Mountain wedge, from which most of the Paleozoic rocks were removed during the Mesozoic-early Tertiary erosion interval. Later in the Tertiary, a reversal of movement elevated the terrane of Paleozoic rocks northeast of the wedge and determined a northwest-trending synclinal trough that extended from North Death Valley through the site of the present Furnace Creek Valley to Amargosa Valley. The Furnace Creek formation was deposited in this trough. In Pliocene time, renewed compression folded the beds in the trough and caused reverse faulting all along the northeast border of the fault zone in the Furnace Creek Valley, where, at many places, Paleozoic rocks are pushed over Furnace Creek beds. Probably the Black Mountain wedge was anticlinally arched and the Amargosa and turtleback thrust faults formed during this time. Faulting accompanied by open folding took place throughout the region after the Plio-Pleistocene (?) Funeral fanglomerate had been deposited upon the Pliocene structure, and was renewed in the fault zone where it has persisted intermittently into Recent time, as is shown by reverse faults and anticlinal domes in Quaternary alluvium in the lower part of Furnace Creek Valley.

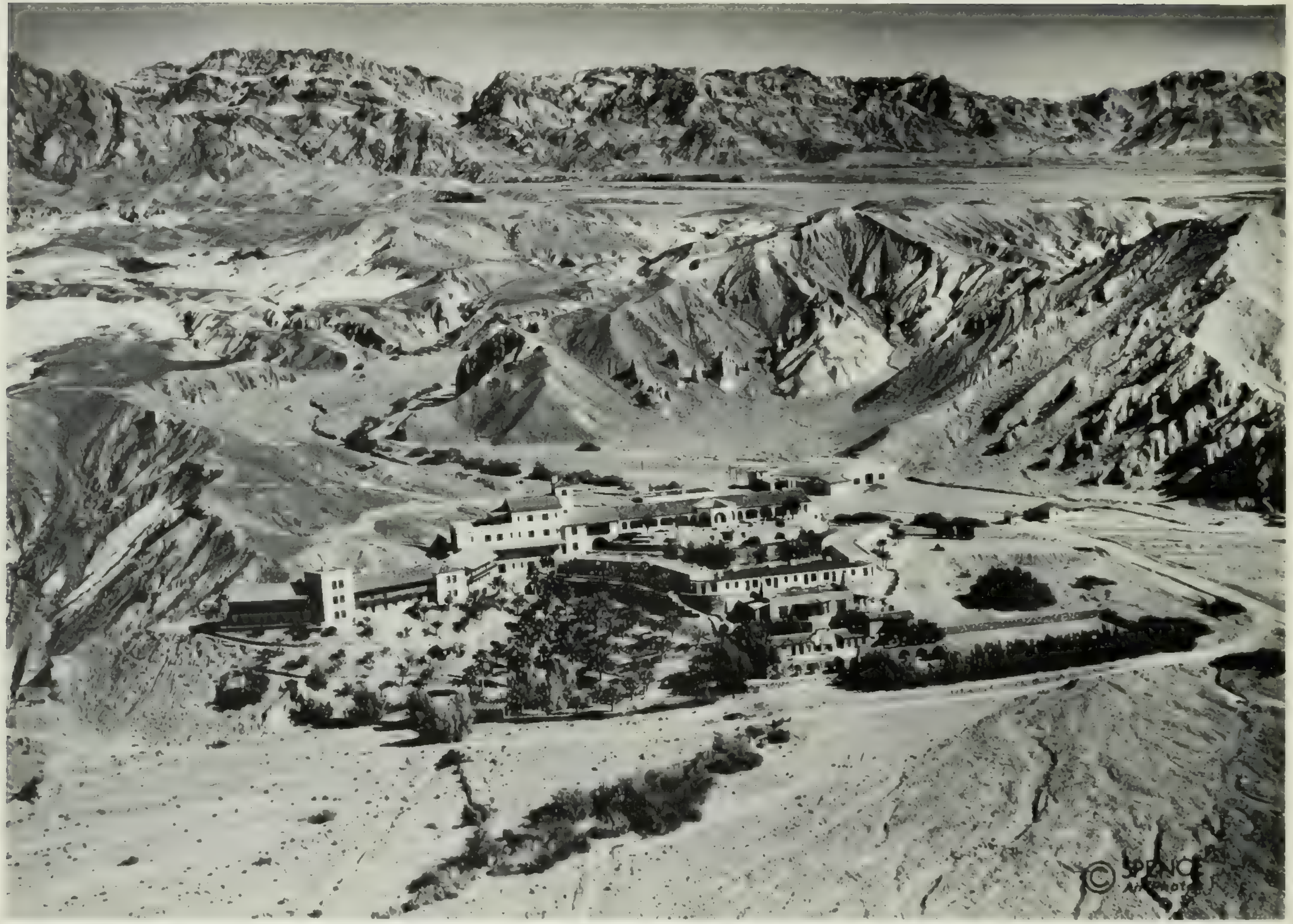

FIGURE 6. View eastward at mouth of Furnace Creek Wash. Furnace Creek Inn in foreground. Bluff upon which Inn is built marks a recent fault scarp. Behind Inn northeast-dipping beds of Funeral fanglomerate overlie similarly dipping strata of Furnace Creek formation. Ridge on skyline is composed of Lower Cambrian strata, which are in fault contact with Furnace Creek strata at Furnace Creek fault zone along base of ridge. *Spence Air Photos.*

Funeral Mountains. The geological features of the Funeral Mountains are imperfectly known, but the mountains are divisible into two structural units. The north half of the range is apparently a northwest-trending anticline whose exhumed core shows a surface that resembles the turtleback surfaces of the Black Mountains. South of Indian Pass the core of the anticline consists of weakly metamorphosed grits and thin beds of dolomite that resemble strata in the lower part of the Johnnie formation as exposed in the Trail Canyon area of the Panamint Range (Hopper, 1947). At the base of Chloride Cliff northwest of Indian Pass the rocks in the core are highly metamorphosed schist, marble, and quartz diorite gneiss that are probably pre-Cambrian in age.

In Boundary Canyon, which separates the Funeral Mountains from the Grapevine Range to the north, disordered masses of Lower Cambrian quartzite and dolomite overlie the metamorphosed rocks, and wedges of the Oligocene Titus Canyon formation (Stock and Bode, 1935) are inset by normal faulting into the Lower Cambrian rocks. Much of the northeastern flank of the range is underlain by a northeast-dipping Tertiary section composed of the Titus Canyon formation, and just beyond the north border of the map area by an overlying Pliocene(?) sequence consisting of tuffs, shales, and sandstones (Stock and Bode, 1935). The Keane Wonder fault, whose trace lies along the southwest base of the Funeral Mountains, resembles the fault along the base of the Badwater turtleback in the Black Mountains (Curry, Contribution 7, Chapter IV).

The south half of the range is underlain by Paleozoic strata in general and isolated patches of the Titus Canyon formation (Stock and Bode, 1935), which here consists chiefly of conglomerate and algal limestone. The Paleozoic strata (fig. 6) dip southeastward and have been broken by complex normal and reverse faulting. The strike of the strata, which east of the divide between Furnace Creek and Amargosa Valley are concealed beneath alluvium, is truncated by the northwest-trending Furnace Creek fault zone. Although formations are repeated several times by faulting, they are in general successively younger from northwest to southeast. For example, the rocks are Lower Cambrian at Echo Canyon, Ordovician in Pyramid Peak, and Mississippian at the southeast tip of the range near Death Valley Junction. The conspicuous white Ordovician Eureka quartzite, repeated several times by the faulting, serves as an excellent marker of the structure.

Resting Spring and Nopah Ranges. The Resting Spring and Nopah Ranges, in the eastern part of the area mapped, are separated by the alluviated Chicago Valley. They are east-tilted fault blocks composed chiefly of Cambrian strata (Hazzard, 1937; Mason, 1948), upon whose back slopes lie remnants of younger Tertiary volcanic rocks. The ranges are essentially homoclinal but are locally cut by cross-faults, most of which trend northwestward. They also are cut by low-angle thrust faults. The frontal fault of each range lies hidden beneath alluvium. In general, the strata strike slightly more westward than the trend of the ranges, so that each range consists of successively younger formations from south to north along the frontal fault at its west base.

In the Alexander Hills, immediately south of the southern end of the Nopah Range, a 7,000-foot section of the Pahrump series overlies earlier pre-Cambrian rocks, at most places with a fault contact (plate 8). The Noonday dolomite, which overlies the Pahrump series apparently with an angular unconformity that has been modified by thrust faulting, successively cuts off units of the Pahrump series as it is traced northward through the Alexander Hills and rests upon earlier pre-Cambrian gneiss at the southern end of the Nopah Range.

Owlshead Mountains. The Owlshead Mountains, which lie southeast of the Panamint Range, are essentially a broad, flat-topped granite dome. Their position between the Death Valley fault zone on the northeast and the Garlock fault zone on the south suggests that the bulging is the result of compression between the two zones of rupture. Much of the granite is overlain by younger Tertiary volcanic rocks that probably are equivalent to the Greenwater volcanics, and by Funeral basalt and fanglomerate.

On the north flank of the dome, opposite the Confidence Hills, the granite cuts strata of the Crystal Spring formation of the later pre-Cambrian Pahrump series, which in one small exposure rests unconformably on earlier pre-Cambrian gneiss. On the south flank of the dome, north of Owl Hole Spring, the granite irregularly intrudes a complex of marble, quartzite, and schist of unknown age mapped tentatively as earlier pre-Cambrian.

The Owlshead Mountains, like the Greenwater Range, are cut by a system of northeast-trending normal faults that are post-Funeral in age. Faulting and warping have produced, in the flat summit of the dome, dry lake basins that have no exterior drainage. Faults of the northeast-trending set are truncated abruptly beneath the alluvium in South Death Valley by the Death Valley fault zone.

Death Valley Trough. The Death Valley trough consists of three segments—a northern segment, mostly outside the area mapped, that trends northwest and lies north of Furnace Creek; a middle segment that trends nearly north and extends from the mouth of Furnace Creek, opposite the north end of the Panamint Range, southward to the mouth of Wingate Wash, opposite the south end of the Panamint Range; and a southern segment that trends northwest and extends southeastward from Wingate Wash to Silurian Dry Lake, at the east

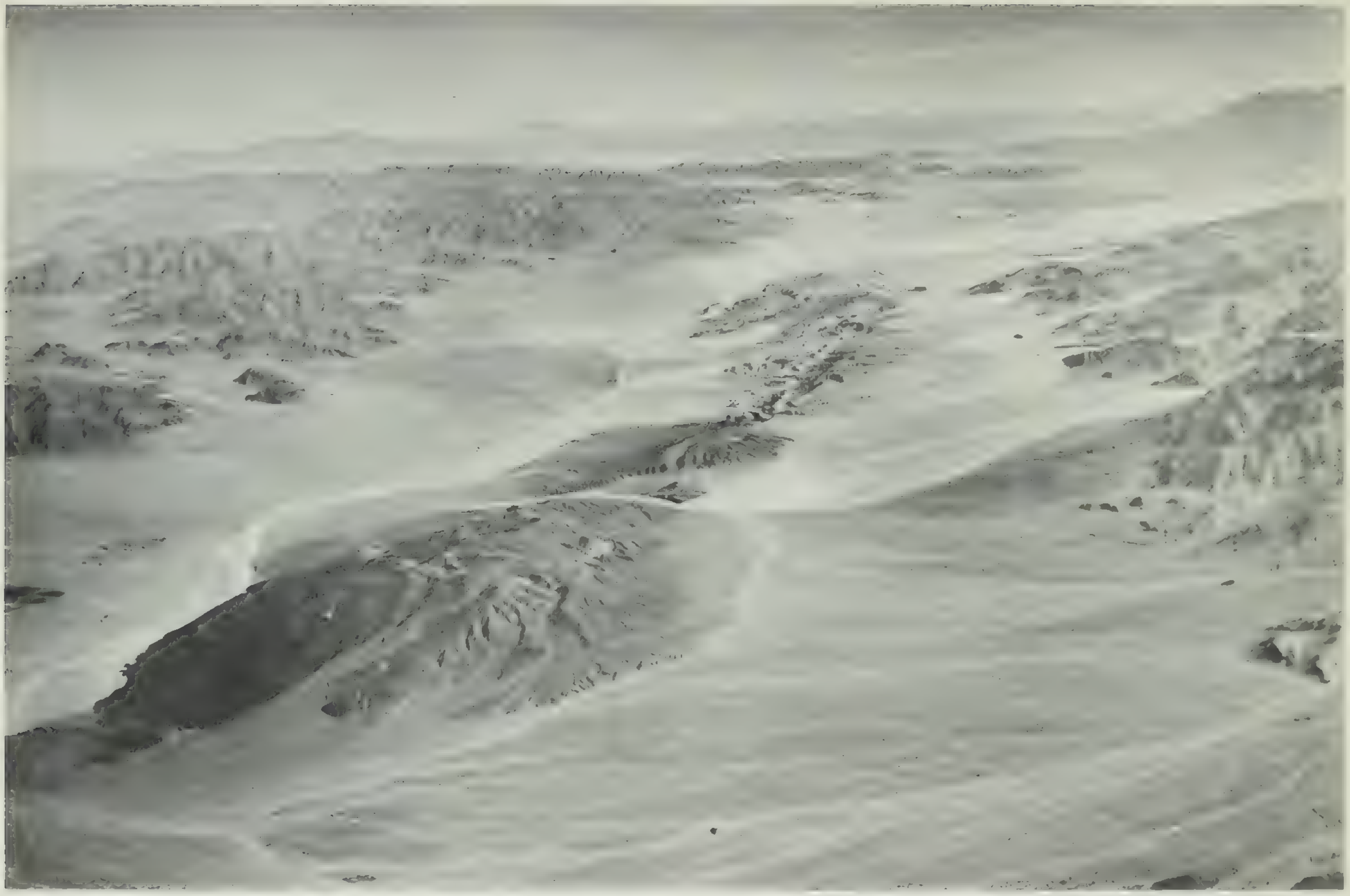

FIGURE 7. View southeastward up South Death Valley, showing Shoreline Hill (lower center) and Confidence Hills (upper center) in the Death Valley fault zone. Valley is bordered at left by southern part of Black Mountains, here underlain mostly by earlier pre-Cambrian metamorphic rocks. Lower east slope of Owlshead Mountains at right is underlain by granite cutting later pre-Cambrian strata of Pahrump series. Amargosa River lies between Confidence Hills and Black Mountains. Confidence Hills consist of tightly folded younger Tertiary strata overlain by broadly folded beds of the Pliocene-Pleistocene(?) Funeral fanglomerate. Both formations are cut along west face of Confidence Hills by recent strike-slip fault in Death Valley fault zone. *Spence Air Photos.*

base of the Avawatz Mountains. The northern segment commonly is known as North Death Valley or the northern arm of Death Valley; the middle segment, which is the deepest part of the trough, constitutes Death Valley proper; and the southern segment commonly is known as South Death Valley.

During probably each of the moist intervals of Pleistocene time a lake occupied Death Valley. The largest of these lakes, named Lake Manly, probably existed during the Tahoe glacial stage (Blackwelder, 1931). It was 116 miles long and at least 600 feet deep. Shore terraces are preserved at several places in the valley, notably at Shoreline Hill, Mormon Point, and a locality about 4 miles south of Furnace Creek Inn (Blackwelder, 1933; Contribution 5, Chapter V, this volume; Clements and Clements, 1953).

North Death Valley extends northwestward from Furnace Creek for more than 50 miles, and the valley floor gradually rises to an elevation of 5,000 feet or more above sea level. It apparently marks a northwestward extension of the Furnace Creek fault zone, which is largely concealed beneath the alluvium of the valley floor. Recent movement along the zone is indicated by scarps in the alluvium at several places northwest of the mouth of Furnace Creek Wash.

Death Valley proper is a fault trough, formed largely in post-Funeral time, between the tilted Panamint Range block and the Black Mountains (plate 8). A steep fault scarp (Curry, Contribution 7, Chapter IV) forms the west face of the Black Mountains for the length of this segment of the Death Valley trough. Movement along this fault has been recurrent, probably since pre-Funeral time (Noble, 1941, pp. 989, 990). The recency of the latest faulting is shown by small scarps that break the alluvial fans and by the small volume of material in the alluvial fans at the base of the scarp, in contrast with the large volume in the huge fans extending outward from the Panamint Range (figs. 2 and 3). The fault truncates the strike of all of the Tertiary strata in the west face of the Black Mountains north of Badwater. South of Badwater, the fault follows the base of the turtleback surfaces at most places. Striae on the fault surface nearly everywhere dip 30° NW. and indicate that the movement of the block east of the fault was relatively southward and upward. This fault appears to be part of a major strike-slip zone, the Death Valley fault zone, that is assumed to lie beneath the Quaternary deposits on the floor of Death Valley proper (plate 8).

South Death Valley lies between the Owlshead and Avawatz Mountains on the southwest and the Black Mountains on the north. The Death Valley fault zone, 2 to 4 miles wide, occupies the axis of the valley but is concealed at most places beneath Quaternary alluvium. The Confidence Hills are a long, narrow belt of tightly folded younger Tertiary rocks in the middle of the zone. Echelon folds of similar rocks southeast of the Confidence Hills in the axis of the valley also mark the zone.

The Death Valley fault zone is well exposed just north of the Avawatz Mountains, where it contains two continuous narrow wedges composed mostly of highly brecciated pre-Tertiary rocks (fig. 8). The wedges are separated by steeply dipping faults from long, narrow belts of intensely folded younger Tertiary rocks. These structural features indicate great compression; they are similar to those that mark the San Andreas fault zone about 120 miles to the southwest (Noble, 1953, 1954). The material in the northern wedge resembles the Virgin Spring phase of chaos, and consists of blocks of the Pahrump series and Noonday dolomite. The southern wedge is chiefly a megabreccia of granite, but 2 miles northwest of Sheep Creek it is a chaotic jumble of huge fault blocks of granite, red conglomeratic sandstone, and Tertiary volcanic rocks, the whole identical in lithology and structure with the part of the Jubilee phase of the chaos north of Ashford Mill, already described. At many places the faulted rocks in the zone are overlain by Funeral fanglomerate, which is itself folded and faulted, but much more gently than the pre-Funeral Tertiary rocks.

Several lines of evidence indicate that the Death Valley fault zone is a great strike-slip fault like the San Andreas and Garlock faults and that the horizontal component of movement is even greater than the vertical, although the total amount of movement is unknown. In the Confidence Hills (fig. 7) a fault in the zone has offset stream courses in such a way as to indicate that the land east of the fault zone has moved relatively southward with respect to the land on the west.

The 30° northeasterly dip of striae on the fault along the east margin of Death Valley indicates that the Black Mountain wedge east of the fault has moved relatively southward and upward. And a horizontal movement measureable in miles is suggested by the distribution of rocks of the Pahrump series on opposite sides of the fault zone: rocks of the Pahrump at Galena Canyon west of the fault zone lie at least 12 miles farther north than any exposures of similar rocks east of the zone.

Leach Trough from Leach Lake to Cave Spring Wash. The segment of the Garlock fault zone that extends from Leach Lake eastward to Cave Spring Wash marks the easternmost part of Leach trough. Here the Garlock fault zone is structurally similar to the Death Valley and San Andreas fault zones, and consists of long, narrow wedges of brecciated pre-Tertiary rocks separated by faults from belts of complexly folded Tertiary rocks, the whole overlain unconformably by the Funeral fanglomerate, which is itself faulted and gently folded and the folds arranged en echelon. The brecciated

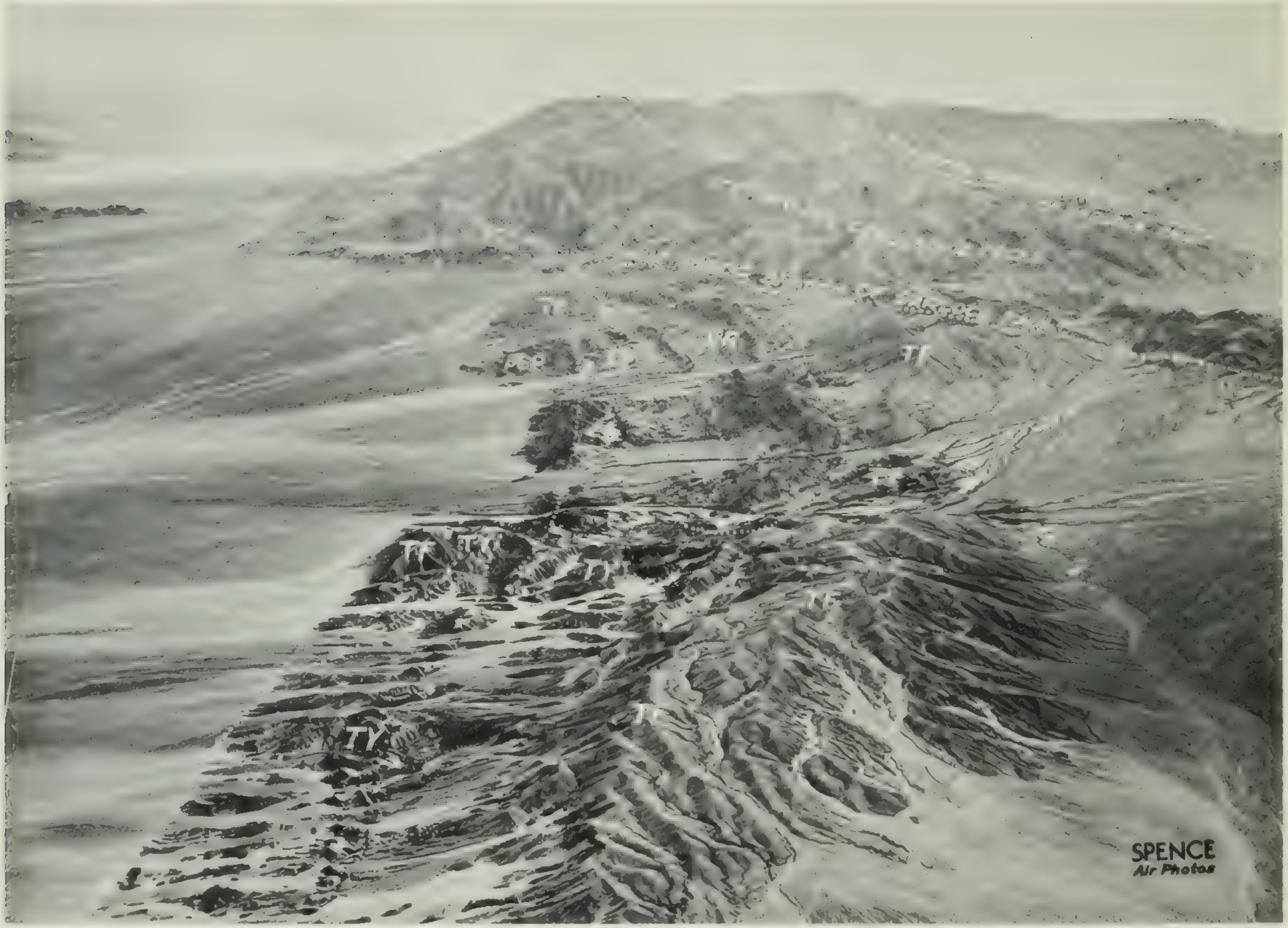

FIGURE 8. View southeastward in South Death Valley along Death Valley fault zone (center foreground) showing junction of Death Valley and Garlock fault zones at north base of Avawatz Mountains (crest of mountains is skyline in background). Cave Spring Wash crosses Garlock fault zone at right of view and crosses Death Valley fault zone at center of view. Death Valley fault zone consists of parallel slivers bounded by high-angle reverse faults. One sliver (A) is composed mostly of disordered blocks of the later pre-Cambrian Crystal Spring formation that resemble the Virgin Spring phase of chaos. Another sliver (GR), which consists of blocks of granite, conglomeratic sandstone, and volcanic rocks, resembles the Jubilee phase of chaos. These are interlayered with slivers of highly folded younger Tertiary sedimentary rocks (TY). Funeral fanglomerate (TF) overlies all the older rocks and is broadly folded. *Spence Air Photos.*

wedges, however, contain no rocks identifiable as belonging to the Pahrump series, and in this respect they differ from the wedges in the Death Valley fault zone.

That the land south of the Garlock fault zone has moved 8 to 12 miles eastward with respect to the land north of the fault is suggested by the fact that the marble-bearing earlier pre-Cambrian(?) rocks near Owl Hole Spring in the Owlshead Mountains north of the zone match similar rocks at Cave Spring Wash, within the zone. Four miles southeast of Owl Hole Spring and lying just north of the Leach Lake fault in the Garlock fault zone, a wedge of huge, chaotic fault blocks is exposed for about 6 miles. The blocks, most of them hundreds of feet in diameter, are granite, metavolcanic, and schistose rocks like autochthonous rocks that crop out south of the Garlock fault zone several miles southeast of the wedge. This apparent offset of lithologically similar rocks also suggests horizontal movement on the Garlock fault zone.

The Death Valley and Garlock fault zones meet in a small, alluvium-covered area just west of Sheep Creek, so that their relations one to the other are concealed. They meet at an angle so acute that it is impossible to be certain whether one fault zone is cutting the other or whether they are contemporaneous. Both are recurrent faults. If the largest horizontal movement on the Death Valley fault zone is more recent that that on the Garlock, the curvature of the Garlock fault zone toward the Death Valley fault zone may be the result of drag on the Death Valley fault zone.

Owl Hole Wash. Owl Hole Wash is an alluvial embayment between the Garlock fault zone on the south, the Owlshead Mountains on the north, and the Death Valley fault zone on the northeast. Underlying the alluvium are poorly exposed folded and faulted Tertiary rocks whose structure is exceedingly complex, apparently because they form a wedge tightly pinched between the two fault zones.

Wingate Wash. Wingate Wash, lying between the Owlshead Mountains on the southeast and the southern end of the Panamint Range on the northwest, coincides with a syncline in younger Tertiary volcanic rocks and the unconformably overlying Funeral fanglomerate. The volcanic rocks probably are equivalent in age to the younger Tertiary Greenwater volcanics. South of the wash they dip northwestward from the granitic dome of the Owlshead Mountains. The overlying fanglomerate dips less steeply. North of the wash the volcanic rocks are complexly folded, but at most places they dip toward the wash. At the mouth of the wash are exposures of algal limestone of Tertiary age whose relation to the volcanic rocks is undetermined but which probably represent a sedimentary part of the younger Tertiary Furnace Creek formation. In late Pleistocene time, Wingate Wash is believed to have carried to Death Valley the glacial drainage that formed lakes in Owens, Searles, and Panamint Valleys.

Amargosa Valley. The Amargosa Valley is a north-trending, alluvium-filled trough between the Greenwater Range and the Dublin Hills on the west, and the Resting Spring Range on the east. It is assumed to coincide with the southern extension of the Furnace Creek fault zone, although for most of its length it is hidden beneath Quaternary alluvium. Hot springs in the lower Furnace Creek Valley and at Shoshone and Tecopa in Amargosa Valley are aligned along the fault zone, and rocks of pre-Tertiary age that are locally exposed within the zone south of Tecopa are highly shattered.

Remnants of basalt of the Funeral fanglomerate lie on the ranges bordering the Amargosa Valley on the west, and extend to the valley floor at Shoshone. After the Funeral was deposited, the valley was depressed by faults along the base of the Resting Spring Range, and a Pleistocene lake occupied the southern end of the valley between Shoshone and Tecopa, where its partly dissected, essentially horizontal beds cover a wide area on the floor of the valley.

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BULLETIN 170

CHAPTER III

HISTORICAL GEOLOGY

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San Francisco — Bulletin 170 — September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER III

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Editorial Note:

CHAPTER THREE outlines the stratigraphic record in southern California, and correlates the major features of sedimentation and life history in this region during Paleozoic, Mesozoic, and Cenozoic time. The record is unusually complete for the Tertiary and Quaternary periods, thanks largely to the preservation of thick sedimentary sections in several basins along and near the present coast. It is distinctly less complete and clear for the Mesozoic era, owing in part to less extensive outcrops of representative strata, and in part to metamorphism of some of these rocks. A record of Paleozoic events can be established from sections in the eastern and southeastern parts of southern California, but corresponding rocks in areas farther west are difficult to identify and interpret.

The eight papers in this chapter deal in various ways with the development of basins, the deposition of sediments in these basins, the evolution of marine and land life as deduced from faunas preserved in the sediments, and numerous problems of stratigraphic correlation. Implicit in all of the discussions is the basic theme of diastrophism, the influences of which have been particularly widespread and significant in this region. Whether the discussion relates to faunal succession, environments of sedimentation, paleogeographic maps, total depth of a given basin of deposition, or to straightforward description of the rocks as they now appear, the pattern and sequence of tectonic events assume fundamental importance. With the interplay of so many different factors and events in the history of the stratified rocks in southern California, it is hardly surprising that more questions are presented in this chapter than satisfactorily can be answered.

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1. CORRELATION OF SEDIMENTARY FORMATIONS IN SOUTHERN CALIFORNIA

By Gordon B. Oakeshott,* Charles W. Jennings,†
and Mort D. Turner †

INTRODUCTION

The correlation chart presented in this paper is intended to provide a simplified framework for understanding of stratigraphic relations that are discussed elsewhere in this volume. No attempt has been made to include all of the stratigraphic names that are used in southern California, or even to note all of the names referred to in this volume; it is hoped, however, that the 192 named sedimentary units that do appear in the chart will suffice to show the principal stratigraphic relationships in the region. More specifically, the chart is intended to indicate the sequence of lithologic units in twenty selected areas and to place those units as accurately as possible in the accepted time framework. The general area covered by the chart is that part of southern California between the Mexican boundary and an irregular line that lies just north of Santa Maria, Cuyama Valley, Kettleman Hills, Bakersfield, southern Owens Valley, and southern Death Valley.

In setting up the relatively simple box-form correlation chart of sedimentary formations covering most of southern California (plate 1), the senior author chose six major column headings that represent major geomorphic provinces designated on the State geologic map published by the Division of Mines in 1938. Twenty columns, including two to five for each province, were selected to give representative samples of the stratigraphy of the entire region. Other important considerations in the selection of these columns were the availability of published information and the completeness of the stratigraphic section in each area.

Valuable suggestions and contributions to the chart were made by Thomas L. Bailey, D. F. Hewett, Richard H. Jahns, Thane H. McCulloh, Bennie W. Troxel, A. O. Woodford, and Lauren A. Wright. Full advantage was taken of previously published data, and also of much new information that appears elsewhere in this volume. Revision of the chart was made repeatedly over a period of several months. Considerable weight was given to recently published correlation charts that represent the work of committees of geologists, such as the chart of Easton, et al. (1953) and those of the American Association of Petroleum Geologists (1952). The authors recognize that geologists are not in complete agreement with respect to many stratigraphic correlations in southern California, and the chart here presented represents an effort to reconcile as many differences in terminology and points of view as possible. The senior author accepts the primary responsibility for the chart in its final form.

EXPLANATION OF CHART

Arrangement. The twenty columns, arranged under six major geomorphic provinces, appear from left to right in a roughly geographical order, so that similar stratigraphic columns in nearby areas are adjacent. Thus, the stratigraphic columns can be followed in a broad, clockwise sweep eastward from the Santa Maria basin across the State to Death Valley, thence southward to Imperial Valley and westward to coastal San Diego County, and thence northwestward to the Santa Ynez Mountains. Each column refers to part of a sedimentary basin and its margins. All the formations in a single column are not necessarily observable in a single small area, as each column is a composite for an area of moderate to large extent.

Geologic Units. The 192 names of geologic units included in the chart are lithologic, rather than time or faunal divisions. Each is a mappable unit, and actually has been shown on at least one geologic map. Only units that appear in outcrop have been included.

The authors would have preferred to use only those unit names that are acceptable to the Geologic Names Committee of the United States Geological Survey, and consistently to follow the principles set forth by the American Commission on Stratigraphic Nomenclature (Stratigraphic Commission, 1947, 1948, 1949), but this proved to be impracticable in a chart of maximum possible usefulness. Regrettably, therefore, several parts of the chart violate the best principles of stratigraphic nomenclature, and numerous terms are included because of their common and well known local usage. In the choice of names of geologic units, great weight has been given to: (1) published geologic mapping; (2) wide usage and general understanding by professional geologists working in the field; and (3) published recommendations of geological committees or groups. However, it has seemed worth while to include a *few* names that do not represent any of these categories.

Symbols. Conventional lines and symbols are used, and hence require little explanation. A dotted pattern indicates the nonmarine units. An attempt has been made to show clearly recognized unconformities by wavy lines, but a straight line does not mean that a local unconformity does not exist. A broken horizontal line indicates some uncertainty as to the time range of the unit; greater uncertainties are suggested by arrows and question marks.

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Sources of Information. The names that appear at the tops of the columns do not indicate responsibility for the contents of the columns, but do represent the principal references that were used in setting up the stratigraphic successions. These sources of information, as well as nearly a hundred others, are listed alphabetically by author at the end of this paper. The list of references is intended to serve as a useful guide to the published record on the stratigraphy of southern California; it is not complete, however, and the omission of any paper is not intended to imply a judgment as to its significance.

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2. ROCKS OF PALEOZOIC AGE IN SOUTHERN CALIFORNIA*

By Charles W. Merriam †

INTRODUCTION

Rocks of Paleozoic age are known to occupy large areas in southern California east of the crest-line of the Sierra Nevada. They occur in three principal subprovinces that differ with respect to initial fullness of stratigraphic section and in the extent to which plutonic intrusion and metamorphism have obscured or destroyed the record of the Paleozoic era. The subprovinces in which rocks of Paleozoic age occur are: (1) Inyo-Death Valley region, (2) Mojave Desert, and (3) Transverse Ranges. In certain other regions, such as the southern Sierra Nevada, the Tehachapi Mountains, the Peninsular Ranges, and the Colorado Desert, rocks of Paleozoic age with little doubt lie hidden among the metasedimentary rocks; here satisfactory fossil dating is yet to be achieved.

While these southern California subprovinces of Paleozoic age represent rather arbitrary divisions, it is quite probable that significant features of each region stem from geographic diversity of Paleozoic time and are not to be ascribed wholly to subsequent effects of intrusion, metamorphism, and erosion of older strata. One is even led to speculate that such an existing geologic boundary as the Garlock fault zone, marginal to the Mojave Desert, has, in a very broad sense, inherited its trace from a Paleozoic geographic lineament. For the Mojave, in seeming lack of Ordovician and Silurian strata and absence or great attenuation of Devonian rocks, recalls the western Arizona-Colorado Plateau paleogeographic province; that it may be built upon a western salient of a large isostatically unstable mass frequently emergent during Paleozoic time is conceivable. By way of contrast the neighboring Inyo-Death Valley region, north of the Garlock fault, received a remarkably continuous marine column during Paleozoic time, embracing the central Great Basin geosynclinal sequence almost completely.

Much of the southern California section of Paleozoic age is a matter for investigation by students of igneous intrusion and metamorphism, for in the metasedimentary rocks generally the likelihood of finding specifically identifiable fossils is not encouraging. Certain metasedimentary rocks, particularly marbles and quartzites of the southern Sierra, Tehachapi Mountains, Transverse Ranges, and Peninsular Ranges, have long been viewed as possessing the "Paleozoic look." In the absence of fossils such criteria as relative ages of granitic intrusion and periods of metamorphism assume major historical importance, surpassed only by specific age determinations on the basis of radioactive elements. Certain of these marbles indicate organic activity, usually in the form of supposed crinoidal debris (Miller, 1946). Most valid fossil evidence applicable to metasedimentary rocks from the western Mojave Desert southward through the Peninsular Ranges points to Mesozoic age (Triassic) rather than Paleozoic. However, with established Triassic rocks as a datum, it is probable that presence of pre-Triassic systems and therefore possibly rocks of Paleozoic age can ultimately be established.

Considering areal distribution of known and inferred rocks of Paleozoic age in the light of paleogeographic theory (Longwell, 1950), it appears probable that nearly all of southern California was from time to time covered by Paleozoic seas. Marine waters believed to have occupied the central Great Basin seaways almost continuously during Paleozoic time probably found entry to the interior across portions of southern California, over the southern Sierra and Mojave regions. Only occasionally in post-Cambrian time is marine ingress to the Great Basin province believed to have taken place from the east across the Arizona region.

The Cambrian system in southern California has been the subject of great interest and active study. Through pioneering researches of Walcott (1895), the Cambrian section of Waucoba Canyon in the northern Inyo Mountains became widely known, in fact almost symbolic for American Lower Cambrian rocks. In subsequent years Cambrian sections east of Death Valley and in the eastern Mojave Desert became the subject of special study by Clark (1921), Resser (1928), Hazzard (1933, 1938), and Mason (1935, 1948). Ordovician, Silurian, and Devonian systems until recently received very little attention, being in fact unknown at many localities where other rocks of Paleozoic age are recognized. Carboniferous and Permian systems are together more widespread in southern California than the older systems of the Paleozoic era. In areas of Cambrian exposure these younger rocks of Paleozoic age are likewise generally represented. Elsewhere, as in the southern Mojave region and in the Transverse Ranges, Carboniferous and Permian are the only systems of Paleozoic age known to have been dated with certainty by fossils. Carboniferous and Permian systems are well developed in the Inyo-Death Valley region as well as in the eastern Mojave (Thompson, et al., 1946), and include a rather remarkable representation of fusulinid-bearing rocks, which have in recent years engaged attention of several investigators.

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* Publication authorized by the Director, U. S. Geological Survey. Although this paper has been edited for consistency in usage, the geologic nomenclature and terminology employed do not agree with that accepted by the U. S. Geological Survey.

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In this brief review two southern California regions of Paleozoic age are worthy of fuller treatment: the Inyo-Death Valley region and the Mojave Desert. Adjoining areas in which the record is meager or lacking are mentioned incidentally.

THE INYO-DEATH VALLEY REGION

The Paleozoic section of the Inyo-Death Valley region is extraordinary in both the stratigraphic and the paleontologic sense, having a thickness in the Inyo Mountains of the order of 23,000 feet. From Lower Cambrian to Upper Permian the column appears to show few major gaps or unconformities. From the Inyo Mountains through Death Valley to the Nopah Range and eastward to the eastern margin of the central Great Basin geosyncline, strata overlap and thicknesses decrease in most parts of the post-Cambrian section. North and northeast of the Inyo Mountains direct marine connections with the central Nevada region during much of Paleozoic time are indicated by their intimate faunal relationship and in some instances by a striking lithologic similarity. Proximity of the Inyo Mountains to the Sierra Nevada batholith virtually eliminates the possibility of following relations of strata of Paleozoic age westward. To the south, through the Argus Range and large parts of the Panamint Range, only Carboniferous and Permian rocks are known with assurance, though it is probable that strata of older Paleozoic age will be found beneath.

Lower Cambrian rocks of the northern Inyo Mountains are included in the Campito sandstone and Silver Peak group, which have a possible combined thickness of 9000 feet. To this may be added certain overlying strata, possibly exceeding 2000 feet, which are of Middle to Late Cambrian age. Beneath the Campito sandstone lie several divisions of questionable assignment, including the Deep Spring formation and the Reed dolomite. Older than the earliest known Cambrian fossil occurrence of the Inyo Mountains area, these units have been viewed as pre-Cambrian by some authorities. In general it may be said that the complex Waucoba area, although the site of classic Cambrian sections, needs a great deal of detailed structural, stratigraphic, and paleontologic investigation to establish clearly relationships with other western Cambrian rocks.

The Cambrian section in the Waucoba area of the Inyo Mountains is supplemented by that in the Ubehebe district (McAllister, 1952) east of the Inyo Mountains, where strata of possible Middle Cambrian (Racetrack dolomite) and Upper Cambrian (Nopah formation) age are represented; these formations serve to relate the Cambrian on the west side of Death Valley to that in the Nopah Range on the east.

The Cambrian section of the Nopah area, as described by Hazzard (1938) and by Mason (1948), includes some eight formations ranging from Lower to Upper Cambrian. The total thickness is reported in excess of 16,000 feet; of this, some 8500 is below the earliest Cambrian fossil zone (*Olenellus*) yet recognized, and has been interpreted by some authorities as pre-Cambrian (Wheeler, 1947). While this view ultimately may prove to have merit, it has as yet no general acceptance (Longwell, 1950), and further knowledge of western Cambrian rocks in relation to world distribution of the system is needed.

Predominance of siliceous clastics in the lower part of the Nopah column recalls the Prospect Mountain quartzite and Pioche shale of the central and southern Great Basin, as well as the Campito sandstone of the Inyo Mountains. The Noonday dolomite, an important lead- and zinc-bearing formation, has been compared with the Lower Cambrian or Upper pre-Cambrian Reed dolomite of the Waucoba area. Increase of carbonates to predominance in the Middle and Upper Cambrian of the Nopah Range is noteworthy, conforming to a well-known conception of an ideal major systemic cycle. Correlation with the Cambrian section of the Mojave region is discussed below.

The Ordovician, Silurian, and Devonian systems (middle Paleozoic) of the Inyo-Death Valley region have of late years become the subject of detailed stratigraphic and paleontologic investigation and for the greater part may be accurately correlated with formations and faunal zones of the central Great Basin.

Ordovician strata of the Inyo Mountains and the northern Panamint Mountains (Ubehebe district) are assigned to well-established Great Basin divisions as follows: Pogonip group (Upper Cambrian to Middle Ordovician), Eureka quartzite (Middle Ordovician), and Ely Springs dolomite (Upper Ordovician).

The Pogonip lends itself to subdivision into several formations with distinctive faunas, the oldest carrying *Eurekia* and *Pseudagnostus* and being Upper Cambrian. Conformably above this is Lower Ordovician with *Kainella* and *Nanorthis*. Middle Pogonip is generally a calcareous, locally cherty, shale with *Kirkella vigilans* (Whittington) and *Hesperonomia*, whereas the upper part is either fairly pure well-bedded to heavy-bedded limestone or dolomite carrying the widespread *Receptaculites* fauna, with the large gastropods *Maclurites* and *Palliseria*.

The Eureka quartzite, an important geologic datum, is sharply set off from underlying and overlying formations by its light gray color and gleaming, vitreous appearance. At many localities it can be partitioned into two or more members on the basis of color and texture differences, the lower part usually being the darker. Locally there is a dark gray argillite or shale at the base which contains fossils of Black River or Trenton age. Uppermost Ordovician (Richmond) faunas are found in the Ely Springs dolomite, which rests with possible disconformity on the Eureka. Usually characterized by its dark gray or almost black, commonly cherty dolomites, the Ely Springs produces a sharp color contrast against the light Eureka.

Silurian rocks of the Inyo-Death Valley region are in the main dolomitic, and attain a thickness of some 1500 feet in the Inyo Mountains and northern Panamint Range, decreasing in thickness east of Death Valley. No satisfactory systemic break between Ordovician (Ely Springs dolomite) and Silurian (Hidden Valley dolomite) has been recognized. Silurian fossils occur in silicified form in the dolomites and locally in limestones. Some of the diagnostic forms at the Inyo and Ubehebe Silurian sections are: *Pentamerus* and other pentameroids, *Atrypa*, *Schizoramma*, *Porpites*, *Halysites*, *Heliolites*, and unnamed cylindrical sponges. Several faunal zones are represented that range from probable Lower Silurian through Niagaran. Within the Inyo Mountains the Silurian includes local limestone facies and thick quartzites. The quartzites, usually interbedded with dolomitic sandstones, reach a thickness of several hundred feet; where carbonate content is low they become quite vitreous, resembling Ordovician Eureka quartzite.

West of Death Valley in the Ubehebe area and Inyo Mountains, Lower Devonian dolomites rest without recognized discordance upon Silurian rocks. East of Death Valley, however, a strong pre-Devonian disconformity is reported (Hazzard, 1938, p. 327), whereas in the Panamint Range near Pinto Peak there is likewise evidence of unconformity at the base of supposedly Devonian sedimentary rocks (Hopper, 1947, p. 408). Lowest Devonian of the Ubehebe area (McAllister, 1952, p. 19) carries a fauna of Oriskany age now widely recognized in the Great Basin. Middle Devonian is represented by the *Stringocephalus* fauna, and in the northern Panamint Range (Ubehebe) Upper Devonian of Devils Gate age, carrying *Crytospirifer*, is present. Varying Devonian facies are well illustrated by the change from prevailing dolomites of the Ubehebe area to marble and limestone in the southern Inyos.

Carboniferous and Permian rocks are extensive west of Death Valley, especially in the Argus Range and southern Inyo Mountains, where they occupy perhaps half the area of sedimentary outcrop.

The Carboniferous section of the Inyo Mountains comprises at least three major units as follows from base upward: Tin Mountain limestone (Lower Mississippian); White Pine group (Mississippian); and an unnamed Pennsylvanian arenaceous limestone.

The Tin Mountain is a dark gray cherty limestone, resting with apparent conformity on Lost Burro formation (Devonian) and carrying a fauna of approximately Madison age. Above the Tin Mountain is the White Pine group, comprising a heterogeneous basal sandy division (Perdido), followed by black shales, siltstones, sandstones, and a few limestone beds. The entire White Pine group in the Inyo Mountains approaches a maximum thickness of 1000 feet, but the thickness varies greatly to the east and southeast, where a great deal more limestone is introduced; east of the Inyo Mountains toward the Argus Range black shales seemingly disappear completely from the White Pine section.

Black shales of the White Pine contain large amounts of plant debris; *Calamites* and fernlike types bespeak proximity of coal-swamp environments. Most of the plant-bearing shales also carry marine fossils in association with the land-plant material. Characteristic are cephalopods of the *Cravenoceras* type, which relate the White Pine to the Caney shale of Oklahoma (Girty, in Kirk, 1918). Limestone beds in the lower White Pine contain the coral *Triplophyllites* and brachiopods of approximately Brazer age. Very widely distributed in the Great Basin, the White Pine group is generally viewed as Middle and Upper Mississippian; the possibility that its upper portion may be Pennsylvanian has been suggested.

The Pennsylvanian system is reprsented in the Inyo area by dark gray impure, muddy, sandy, and chert-pebbly limestones resting conformably on the White Pine group. These rocks have a maximum thickness of about 2200 feet. Intercalations of pinkish or maroon punky-weathering shale are characteristic. Fusulinids are almost the only identifiable fossils known in this division. Three major fusulinid zones are recognizable: (1) A lower zone with *Fusulinella*, above which is (2) the *Triticites* zone, comprising most of the division, and at the top (3) a minor subzone with *Schwagerina* and *Triticites*. The *Schwagerina-Triticites* subzone is introductory to the Permian system.

Permian strata of the Inyo Mountains require wholly revised nomenclature. The names Owenyo limestone and Reward conglomerate apply only to localized units high in the Permian column. Permian strata of the Inyo Mountains thicken and thin rapidly along the strike, ranging in thickness from a few feet to about 2000 feet, and embracing stages from lower Wolfcamp to approximately Word or Phosphoria. Fusulinids are again the characteristic fossils, with three major zones: (1) the lowermost with *Triticites* and *Schwagerina;* (2) a middle zone with *Pseudoschwagerina;* followed by (3) the *Parafusulina* zone. The uppermost faunal zone, that of the Owenyo limestone, carries a brachiopod assemblage with very abundant *Spirifer pseudocameratus* (Girty), just beneath which are beds with *Parafusulina*. Lithologically the strata from the *Pseudoschwagerina* zone to the top of the Permian are heterogeneous, comprising pebbly, sandy, and silty impure limestones, shales, sandstones, and conglomerates. Locally there is a well-defined angular unconformity between this entirely Permian division and the underlying unit, which is mainly Pennsylvanian but paleontologically transitional to Permian at the top. The compressional deformation involved appears thus to have taken place in early Wolfcampian time. In general formations of Pennsylvanian and Permian age in the Inyo Mountains correlate with portions of the Bird Spring formation in southwestern Nevada, which yields comparable Pennsylvanian and Permian fusulinid assemblages (Longwell and Dunbar, 1936).

The Carboniferous and Permian rocks east of Death Valley are less well understood. Strata assigned to Carboniferous consist mainly of Mississippian and Pennsylvanian limestones (Hazzard, 1938). Though no fusulinids are reported, the Pennsylvanian system of the Nopah area probably agrees on lithologic grounds with a portion of the Bird Spring formation in the interval of *Triticites*. Black shales of the White Pine group are unrecognized east of Death Valley; they are believed to be replaced in this direction by limestone facies in accordance with the observed environmental changes between the southern Inyo Mountains and the Argus Range (see also Hopper, 1947, p. 409).

MOJAVE DESERT REGION

Eastern Mojave Desert. Important exposures of rocks of Paleozoic age occur in the eastern Mojave Desert from the Providence Mountains southward to Cadiz (Marble Mountains), and in the southern Mojave east of Victorville. Several outcrops of unfossiliferous marble and quartzite, including those at Oro Grande (Oro Grande series), may possibly be Paleozoic in age. Of interest are numerous scattered occurrences of crinoidal debris suggesting Paleozoic age (Miller, 1946). Such evidence is believed sufficient to indicate wide distribution of sediments during Paleozoic time throughout the Mojave, in areas where intrusion and metamorphism now prevail (see also McCulloh, Contribution 2, Chapter VII).

Systems represented by convincing fossil evidence are the Cambrian, Carboniferous, and Permian. No Ordovician or Silurian record has yet been found, and doubt exists as to presence of Devonian rocks except toward the eastern margin of the Mojave region. In the Providence Mountains, Middle Cambrian rocks are overlain by some 375 feet of dolomite possibly of Devonian age (Hazzard, written communication). Absence or restriction of strata of Middle Paleozoic age in the Mojave Desert would appear to link this region paleogeographically with the Colorado Plateau province, where this part of the column also is absent or greatly attenuated.

Eastern Mojave rocks of Paleozoic age are best understood in the area between Cadiz (Marble Mountains) and the Providence Mountains (Hazzard, 1933; Hazzard and Mason, 1936), where the section is largely of Cambrian and late Paleozoic age. Near Cadiz station on the Santa Fe Railroad, Lower and Middle Cambrian strata rest upon pre-Cambrian crystalline rocks and are overlain by limestones of uncertain age followed by Carboniferous rocks. The section is well shown at the south end of the Marble Mountains 2 miles northeast of Cadiz and at the north end of the Ship Mountains 7 miles east of Cadiz. Lower Cambrian strata are represented by about 600 feet of quartzite, shale, and limestone; partly cross-bedded quartzite at the base rests with marked unconformity on a smooth pre-Cambrian surface of granitic rocks, gneiss, schist, and marble. Mud cracks are present in the topmost quartzite layer. A richly fossiliferous greenish gray shale 40 feet thick rests upon the quartzite; faunas from this zone have been investigated by Resser (1928) and by Crickmay (1933). The following trilobites are reported: *Olenellus fremonti* (Walcott), *O. insolens* (Resser), *O. bristolensis* (Resser), *Paedumias clarki* (Resser), *P. nevadensis* (Walcott), and *P. mohavensis* (Crickmay). The trilobite shales are overlain by limestone with concentrically laminated ovoidal nodules (*Girvanella*) of presumed algal origin. Quartzite, shale, and limestone (Cadiz formation) about 500 feet thick rest upon the algal limestone member. Characteristic of this interval is fine-grained, reddish brown to gray micaceous quartzite with a platy parting; associated micaceous clay shales show worm tracks and ripple marks. Tan-colored oolitic limestone interbeds are cross-bedded. Lying upon the platy quartzite is a 100-foot limestone member carrying Middle Cambrian *Dolichometopus* and *Bathyuriscus*. This limestone is platy and bluish gray, weathering yellowish.

As traced 30 miles north of Cadiz to the Providence Mountains, the platy quartzite and limestone (Cadiz formation) give evidence of Middle Cambrian age with *Zacanthoides*, *Glossopleura*, and *Alokistocare*. Here occur two higher units of possible Middle Cambrian age: Bonanza King formation followed above by the Cornfield Springs. The two formations consist mainly of dark and light gray dolomite with subordinate beds of sandstone, quartzite, and shale. Fossils have not been found in the Bonanza King, but the Cornfield Springs has yielded some fossils.

The eastern Mojave Cambrian section exhibits lithologic facies and faunas widely recognized in the Great Basin but not yet thoroughly understood; precise correlations will no doubt eventually be made with the classic Nevada sections at Pioche and Eureka. Several of the formations in the Providence Mountains including the Cadiz, Bonanza King, and Cornfield Springs have likewise been identified at Nopah east of Death Valley (Hazzard, 1938). The Cornfield Springs at Nopah is overlain by the Nopah formation, which contains *Elvinia* and *Pterocephalia* and is thereby assignable to the Upper Cambrian.

Grand Canyon relationships are found in parts of the Middle Cambrian referred to the Cadiz (Wheeler, 1947; Wheeler and Beesley, 1948), which appear to fall in line with the Bright Angel shale. The Tapeats sandstone in the Grand Canyon, while lithologically comparable to the pre-*Olenellus* quartzites of the Death Valley and

Mojave regions, is believed to be actually much younger, being Middle rather than Lower Cambrian or older.

Carboniferous and Permian strata of the eastern Mojave region are well developed in the Providence Mountains and are reported above Cambrian rocks in the Cadiz area to the south. The Providence Mississippian agrees in considerable part with Monte Cristo limestone at Goodsprings, Nevada (Hewett, 1931), yielding spirifers of the *Spirifer centronatus* and *S. logani* types (Hazzard, 1938). The Pennsylvanian system is predominantly limestone, but it includes sandy limestone, sandstone, and shale with *Dictyoclostus americanus* (Dunbar and Condra), *Juresania nebrascensis* (Owen), and *Spirifer* cf. *S. opimus* (Hall). Locally basal Pennsylvanian contains small black chert pebbles (Hazzard, written communication), which recalls the golfball chert and *Fusulinella* zone of the Inyo Mountains and Ubehebe district (McAllister, 1952). Fusulinids, so abundant in the Pennsylvanian system of the Inyo Mountains, have not been reported in this part of the eastern Mojave section.

Permian limestones of the Providence Mountains (Thompson, et al., 1946) are about 2000 feet thick and apparently unconformable on subjacent Carboniferous rocks. A few thin sandstone interbeds are present. Abundant fusulinids in the lower few hundred feet indicate a Wolfcamp age; among the genera recognized are *Pseudoschwagerina*, *Triticites*, *Schwagerina*, and *Schubertella*. A large *Omphalotrochus* is also present. Recognition of *Parafusulina* suggests that rocks of Leonard age may possibly occur in the Providence Mountains; however, it should be added that this genus occurs in association with *Pseudoschwagerina* in higher Wolfcampian of the Inyo Mountains. Permian of the Providence area is believed to be correlative with the Permian portion of the Nevada Bird Spring and likewise of the lower or Wolfcampian part of the Inyo Mountains Permian column. As the greater part of the Providence section above the lower 400 feet has not yielded fusulinids, it is possible that Middle and Upper Permian may be represented.

The Permian section in the Providence Mountains differs lithologically from that of the Inyo Mountains in being on the whole less arenaceous and in lacking the conglomerates that characterize the upper part of the Inyo column. Maximum thickness of the order of 2000 feet is about the same for both Inyo and Providence Permian sections.

Southern Mojave Desert. The age relationships of the limestone, marble, and quartzite in the vicinity of Oro Grande and Victorville have long been the subject of speculation. At Oro Grande the Oro Grande series (Hershey, 1902) comprises marbles underlain by quartzite at one time considered Lower Cambrian and correlative with the Inyo Mountains section. In the absence of fossils there is, however, no evidence for Cambrian age. East of Victorville a thick limestone conglomerate has yielded determinable fossils of Pennsylvanian or Permian age. The faunas include *Meekella*, *Heritschia*, and large, poorly preserved gastropods probably assignable to *Omphalotrochus*. Stratigraphic relation to the Oro Grande series is not known (see also McCulloh, Contribution 2, Chapter VII).

Northern Mojave Desert. Of particular interest is the thick section of Paleozoic age in the El Paso Range (Dibblee, 1952), just north of the Garlock fault, at the north edge of the Mojave region. Including shales, cherts, conglomerates, and great thicknesses of altered siliceous or hornfelsic deposits, a part of the section is known to be of Permian age on the basis of *Schwagerina*, but the column undoubtedly embraces much more of the Paleozoic era. A great facies change between the El Paso Range and the Inyo Mountains Permian is worthy of note.

NORTHERN SAN BERNARDINO MOUNTAINS

Quartzites, schists, and limestones northeast of Baldwin Lake, northern San Bernardino Mountains, are partly Carboniferous. Three formations have been described (Vaughan, 1922, p. 352); these in ascending order are: Arrastre quartzite, Furnace limestone, and Saragossa quartzite. The Arrastre quartzite is reported conformably overlain by Furnace limestone, with Saragossa quartzite conformable upon Furnace. Cross-bedding in the Saragossa according to Vaughan (1922, p. 352) establishes order of superposition as given. It is pointed out, however, that deformation, intrusion, and metamorphism so complicate the geology that the present position of strata is no reliable criterion of normal stratigraphic order. The Saragossa is pure and saccharoidal, ranging from quartzite to coarse, angular grits and pebble conglomerate; its members are heavy bedded and cross-bedded. The Arrastre quartzite, on the contrary, is impure and mostly thin bedded.

The Furnace limestone is estimated by Vaughan (1922, p. 357) to be 4500 feet thick. It varies from white to nearly black in color, and from fine and compact to very coarsely crystalline in texture. Near granite contacts it is often completely recrystallized to coarse white marble. Fossils collected near the top of the Furnace limestone (Woodford and Harriss, 1928) were determined as more likely Mississippian than Pennsylvanian in age. Collections recently obtained * from the Furnace limestone include *Dictyoclostus*, *Spirifer* cf. *S. centronatus* (Winchell), and large solitary horn corals of the *Caninia* type. These forms appear to confirm a Mississippian age assignment. A limestone with possible small fusulinid "ghosts" was also found, and may be either Pennsylvanian or Permian, though the prevailing small size of the fossils is more suggestive of a Pennsylvanian type. Fossils of the Furnace limestone suggest that the formation is largely if not entirely older than the conglomeratic limestones of the Victorville area.

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* Fossil collections made by James Richmond of the Stanford University Graduate School were referred to the writer for identification.

Quartzite beneath the marble at Oro Grande is reported to be quite pure, as is the Saragossa. In the Inyo-Death Valley region, clean, vitreous quartzite is largely confined to Devonian and older rocks, and is exceptional in Carboniferous or Permian strata. If the Saragossa were actually older, rather than younger than the Furnace limestone, as concluded by Vaughan (1922), there would be agreement here. In contrast, the impure, thin-bedded Arrastre sandstones are compatible with Pensylvanian or Permian rocks of the Inyo-Death Valley region.

THE PENINSULAR RANGES

Extending southward from the Riverside area into the Peninsular Ranges are numerous metasedimentary bodies; some are almost certainly Triassic, others are possibly Paleozoic in age. Prior to alteration the sedimentary rocks appear to have been mainly shales and sandstones (Larsen, 1948, p. 15) with localized limestones such as those represented by marble inclusions in granitoid rocks near Riverside. Triassic dating of these metamorphic rocks is based on analogy with the Triassic Bedford Canyon formation of the Santa Ana Mountains. Schists with interbedded limestones at Domenigoni Valley, near Winchester (Larsen, 1948, pp. 15-16), are possibly older and of Carboniferous age. A fossil of reported Carboniferous age (Webb, 1939) was found at the old magnesite quarry southeast of Winchester. Similar schists possibly of Paleozoic age are reported from the San Jacinto Mountains to the east.

In the Cuyamaca region (Hudson, 1922) the Julian schist has been considered Triassic in age on the basis of petrologic analogy, but it may include older rocks. As pointed out by Larsen (1948, p. 16), certain schists east of Oak Grove Valley give indirect evidence of pre-Triassic age. In this area granite gneiss associated with these schists is very different from rocks of the post-Triassic batholith, and may be allied to the older Stonewall granodiorite (Hudson, 1922, p. 191). According to Larsen (1948, p. 16), "It is believed that the Paleozoic sediments were metamorphosed and intruded by granitic rocks before deposition of the Triassic rocks and that this older metamorphism was more intense than the later metamorphism of the Triassic rocks."

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3. MESOZOIC FORMATIONS AND FAUNAS, SOUTHERN CALIFORNIA AND NORTHERN BAJA CALIFORNIA

By W. P. Popenoe *

This paper summarizes the known distribution and development of the Mesozoic sedimentary formations of southern California, and of Baja California, Mexico, in a coastal strip approximately 30 miles wide, extending between the parallels 34° 30′ and 29° 00′ north. A tentative regional correlation for these formations is suggested, and their inferred position in the standard Mesozoic time scale is indicated. Stratigraphic and paleontologic knowledge of these formations is not as full as could be desired, and for some, especially the Triassic of the Santa Ana Mountains and the Cretaceous of Baja California, it is especially meager. Later work thus will doubtless amplify or alter the interpretations offered here.

In this general region, Mesozoic rocks commonly form the "basement," which is widely concealed by the overlap of younger formations that also appear from place to place as disconnected and isolated patches a few square miles in area. The principal Mesozoic exposures and their relationships to familiar landmarks of southern California and northern Baja California are shown on figure 1. Local stratigraphy, gross lithology and representative thicknesses of the formations, and stratigraphic positions of important faunal assemblages are indicated on the columnar sections of figure 2; the identity and stratigraphic occurrence of about thirty common or diagnostic fossil species are shown on the check list (table 1); and some characteristic Upper Cretaceous fossils are shown in figures 3 and 4.

DISTRIBUTION AND DEVELOPMENT OF THE MESOZOIC ROCKS

Triassic Rocks. Triassic sedimentary rocks have been definitely identified in southern California only from the Santa Ana Mountains east of the city of Santa Ana. Near the crest of the range are great thicknesses of mildly metamorphosed slate and argillite with minor quartzite and thin lenses of limestone. The limestone lenses from the upper part of the section have yielded a sparse fauna including the brachiopod genus *Halorella* and probably the ammonite genus *Juvavites*.[1] Muller considers these to indicate a Norian, Upper Triassic age for the containing beds. Larsen (14, p. 18) has described these metasediments in some detail, has named them the Bedford Canyon formation, and has estimated their maximum thickness to exceed 20,000 feet.

The Santa Monica slate, exposed over a large area in the eastern Santa Monica mountains in western Los Angeles County, has been considered to be of probable Triassic age, owing to its lithologic and stratigraphic similarity to the Bedford Canyon formation. The slate has yielded no fossils, and hence its age is not firmly established.

Jurassic Rocks. Sedimentary rocks of unquestioned Jurassic age are not known to occur in the area discussed in this paper. Dibblee (6, pp. 21-23) notes a small area of Franciscan (?) rocks from a locality just beyond the boundaries of this area, and describes the Honda formation, which has yielded a small pelecypod "*Aucella*,"

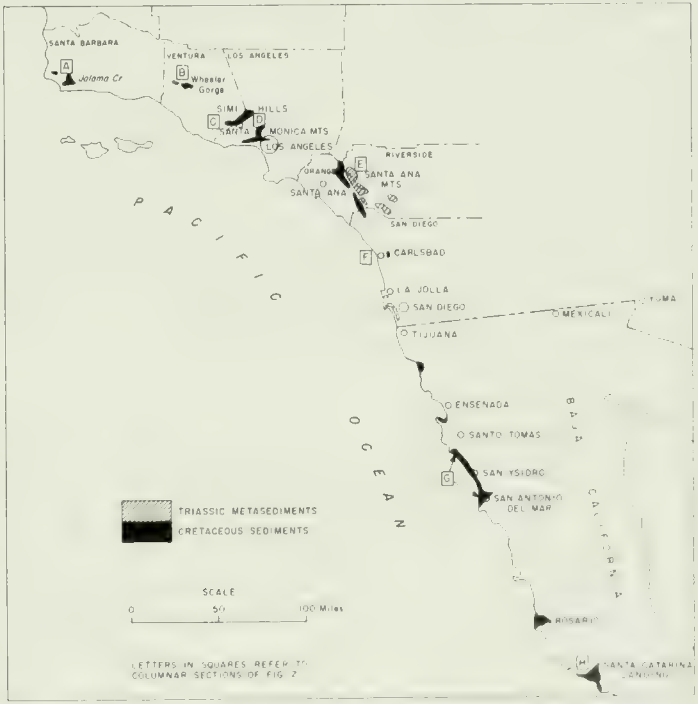

Figure 1. Index map of a part of southern California and northern Baja California, Mexico, showing the principal outcrop areas of Mesozoic sedimentary rocks.

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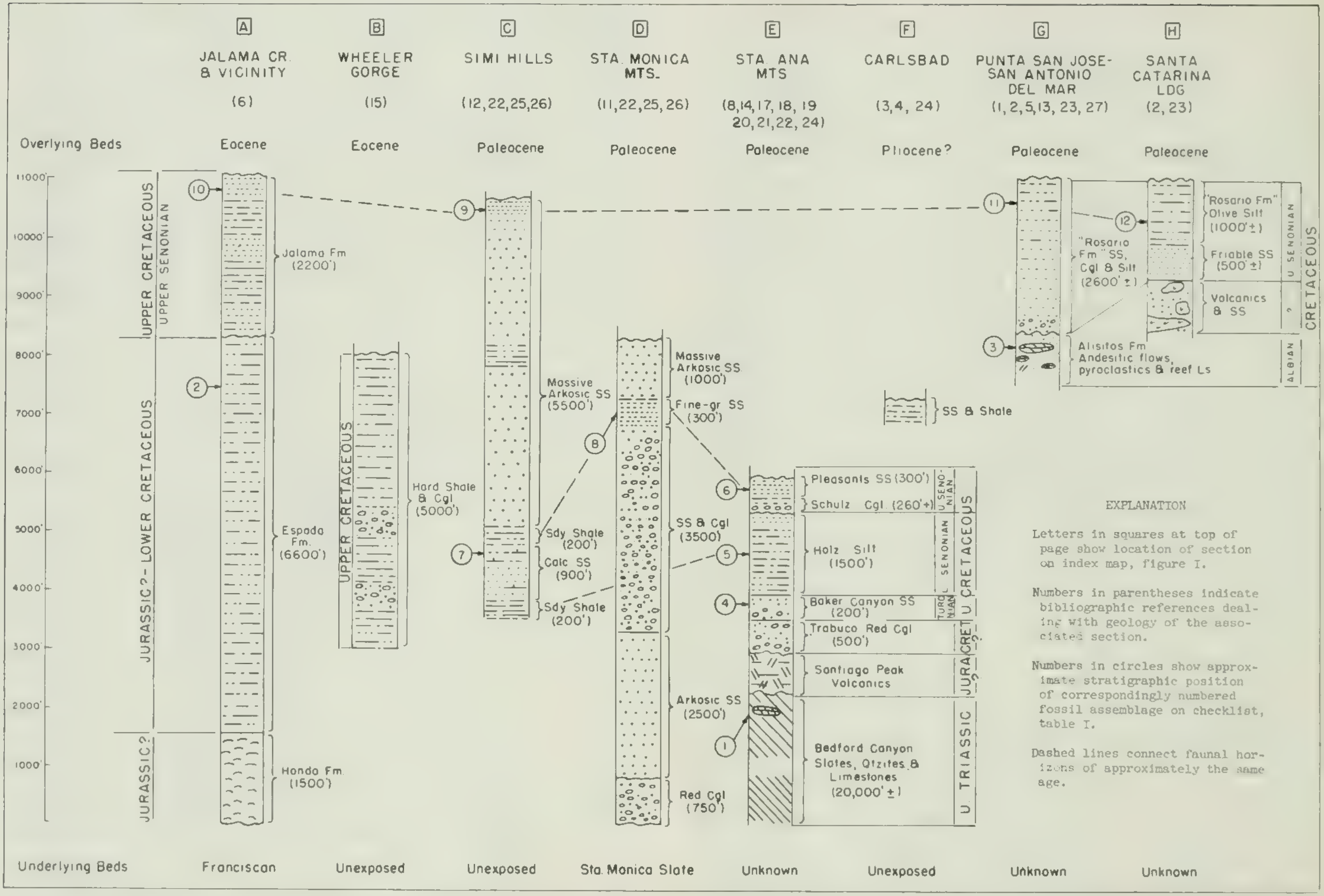
* Associate Professor of Geology, University of California, Los Angeles.

[1] S. W. Muller, personal communication.



EXPLANATION

Letters in squares at top of page show location of section on index map, figure 1.

Numbers in parentheses indicate bibliographic references dealing with geology of the associated section.

Numbers in circles show approximate stratigraphic position of correspondingly numbered fossil assemblage on checklist, table I.

Dashed lines connect faunal horizons of approximately the same age.

FIGURE 2. Generalized columnar sections of Mesozoic sedimentary rocks in important outcrop areas of southern California and Baja California, Mexico.

near "*A.*" *piochii* and which may be Jurassic in age. The outcrop area of the Honda is too small to show on the index map (fig. 1). Its Jurassic age seems probable, but is not yet proved.

Lower Cretaceous Rocks. From the general vicinity of Jalama Creek in western Santa Barbara County, Dibblee (*op. cit.*) describes outcrops of the Espada formation, which includes as much as 6,800 feet of brown carbonaceous shales with some thin seams of sandstone. The upper part of the formation has yielded specimens of "*Aucella*" *crassicollis*, suggesting a horizon somewhere in the Neocomian. From a different locality, shales resembling the Espada have yielded specimens of "*Aucella*" *piochii*, suggesting a late Upper Jurassic age. It thus seems possible that this formation may range in age from Upper Jurassic through the Neocomian. With this exception, beds of Neocomian age are not definitely known to crop out in the area treated in this report.

Middle Cretaceous Rocks. From place to place in northern Baja California, at least as far south as the 29th parallel, large exposures of a very thick series of metasediments interlayered with volcanic rocks have been described by several reconnaissance workers. This series has been designated the San Fernando formation by Beal (5, pp. 38-40), the Alisitos formation by Santillan and Barrera (23, p. 9), and probably is at least in part included in the San Telmo formation of Woodford and Harriss (27, p. 1306). The thickness and areal extent of these metasediments are undetermined, but are believed to be great.

Fossils from this series have been mentioned by earlier workers (Beal, *op. cit.*), but with no precise age assignment beyond "Middle Cretaceous." Allison (1), and Kirk and McIntyre (13) have collected large numbers of species of well-preserved gastropods, pelecypods (including a variety of rudistids), and echinoids from beds in coastal exposures between Ensenada and San Antonio del Mar. The fauna is totally new, and is unlike anything previously found in the Pacific Coast Cretaceous faunas. The faunal relationships appear to be closest to middle Albian assemblages of Texas, Central and South America, southern Europe, and other localities in the Eastern Hemisphere.[2]

Upper Cretaceous Rocks. Upper Cretaceous marine sediments are widely distributed in southern California and northern Baja California, and constitute most of the outcrop areas shown on the index map. Rock types include a variety of coarse clastics, with considerable thicknesses of silts. No true limestones and probably no interbedded volcanics are associated with these clastics. The age-range of the sediments is not yet precisely known, but probably lies between some horizon in the Turonian below, and late Campanian or early Maestrichtean above. Cenomanian rocks are not known to occur in southern California, although both the unfossiliferous Trabuco formation of the Santa Ana Mountains and a red conglomerate of similar stratigraphic position in the Santa Monica Mountains may belong to this stage.

Table 1. Checklist of some common and characteristic fossil species from the Mesozoic formations of southern California and Baja California, Mexico. Locality numbers correspond to the same numbered localities in circles beside the columnar sections, figure 2.

SPECIES	LOCALITIES											
	1	2	3	4	5	6	7	8	9	10	11	12
1. Juvavites sp.[1]	x											
2. Halorella sp.	x											
3. "Aucella" crassicollis Keyserling [2]		x										
4. Nerinea (Plesioptygmatis) sp.[3]			x									
5. Orbitolina texana Roemer			x									
6. Turritella aff. t. seriatimgranulata Roemer			x									
7. Acteonella fusiformis Coq.			x									
8. Cassiope sp.			x									
9. Acteonella oviformis Gabb				x								
10. Ampullina pseudoalveata (Packard)				x								
11. Glycymeris pacificus (Anderson)				x								
12. Trigonarca californica Packard				x								
13. Cucullaea gravida (Gabb)				x								
14. Lima beta Popenoe				x								
15. Trigonia sp, cf. T. evansana Meek				x								
16. Turritella chicoensis Gabb					x							
17. Ampullina packardi Popenoe					x							
18. Glycymeris veatchii var. (Gabb)					x							
19. Cymbophora gabbiana (Anderson)					x	x	x	x				
20. Crassatella spp. cf. C: lomana Cooper					x	x	x	x				
21. Trigonia ynezana Packard					x	x	x	x		x		
22. Turritella chicoensis perrini Merriam					x							
23. Gyrodes expansa canadensis Whiteaves					x	x	x	x	x		x	x
24. Perissitys brevirostris (Gabb)					x	x	x	x				
25. Calva bowersiana (Cooper)						x	x	x				
26. Clisocolus cordatus Whiteaves					x	x	x		x			
27. Cucullaea youngi Waring					x	x	x	x				
28. Metaplacenticeras spp.						x	x	x				
29. Pachydiscus spp. (coarse-ribbed giants)						x	x					
30. Pachydiscus peninsularis (Anderson and Hanna)												x
31. Pachydiscus catarinae (Anderson and Hanna)									x		x	x
32. Cophocara stantoni Stewart									x			x
33. Calva "steineyi" Hertlein MSS name									x	x	?	

[1] Determinations loc. 1, by S. W. Muller.
[2] T. W. Dibblee, Jr. (5, p. 23).
[3] Determinations loc. 3 by E. C. Allison.
All other determinations by W. P. Popenoe.

The Baker Canyon sandstone of the Santa Ana Mountains contains a distinctive fauna of thick-shelled mollusks, which also is found in northern California associated with ammonites of the genera

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[2] Allison, E. C., personal communication.

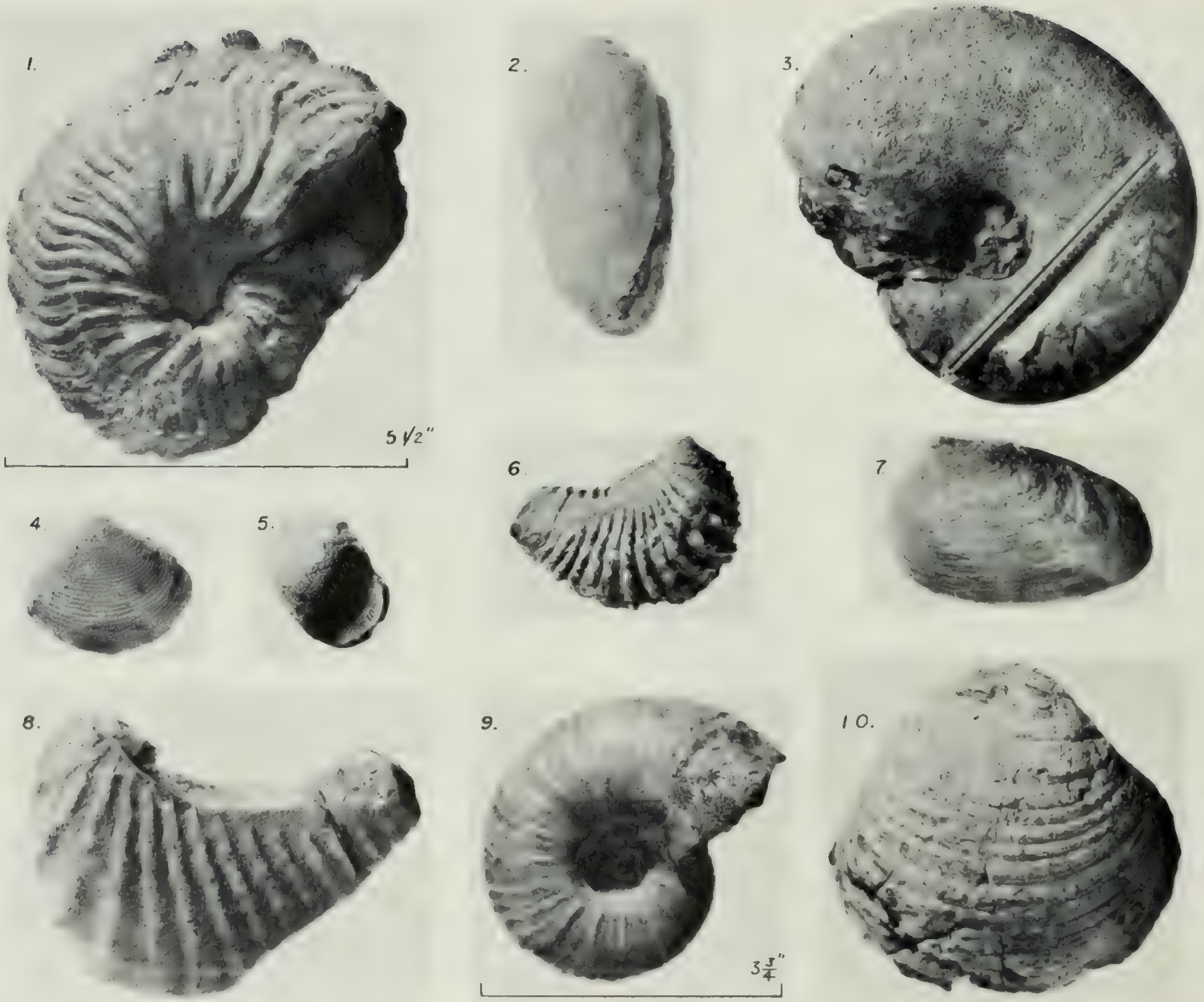

FIGURE 3. Cretaceous species from southern California and Baja California. All illustrations are natural size except where scale is shown. 1. *Metaplacenticeras sanctaemonicae.* 2. *Acteonella oviformis.* 3. *Pachydiscus catarinae?* 4. *Cymbophora gabbiana.* 5. *Ampullina packardi.* 6. *Trigonia cf. evansana.* 7. *Crassatella cf. lomana.* 8. *Trigonia yuczana.* 9. *Pachydiscus peninsularis.* 10. *Calva bowersiana.*

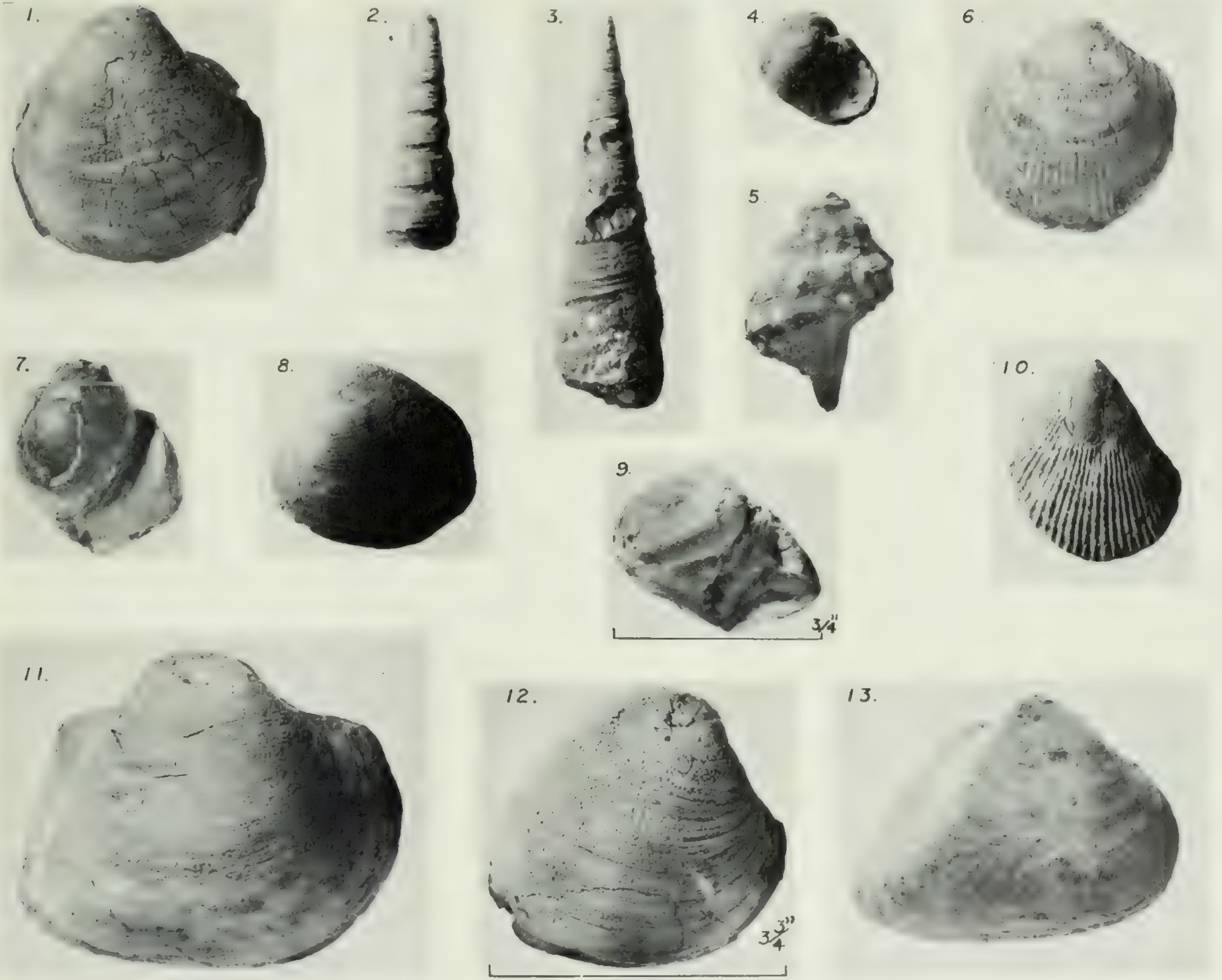

FIGURE 4. Cretaceous species from southern California and Baja California. All illustrations are natural size except where scale is shown. 1. *Clisocolus cordatus.* 2. *Turritella chicoensis.* 3. *Turritella chicoensis perrini.* 4. *Euspira shumardiana.* 5 *Perissitys brevirostris.* 6. *Glycymeris veatchii* var. 7. *Ampullian pseudoalveata.* 8. *Calva regina.* 9. *Gyroides expansus canadensis.* 10. *Lima beta.* 11. *Cucullaea youngi.* 12. *Calva "steineyi."* 13. *Trigonarca californica.*

Romaniceras, *Parapuzosia*, *Gaudryceras ?*, and *Tragodesmoceras*.[3] This suggests a Turonian age for the fauna.

Directly overlying the Baker Canyon sandstone of the Santa Ana Mountains is the Holz silt member, in the upper part of which a molluscan fauna includes rare specimens of the ammonite genus *Canadoceras*. This probably indicates an upper Senonian age for this part of the Holz member. Correlatives of the Baker Canyon sandstone and most of the lower part of the Holz silt member have not been recognized with certainty elsewhere in southern California, but they may be present in the lower, unfossiliferous part of the Cretaceous section in the Santa Monica Mountains. As suggested in the columnar sections (fig. 2), the basal shale member of the Cretaceous section in the Simi Hills may be equivalent to the upper Holz silt.

The Pleasants sandstone of the Santa Ana Mountains has yielded a prolific molluscan fauna, including the ammonites *Metaplacenticeras*, heavy-ribbed *Pachydiscus* (?), and fragments of *Nostoceras*-like species. This assemblage also occurs near the top of the Cretaceous section of the Santa Monica Mountains (locality 8) and near the base of the section in the Simi Hills (locality 7).

The youngest Cretaceous rocks thus far recognized in the area are those of the so-called Rosario formation of Baja California, and the highest beds exposed in the Cretaceous section of the Simi Hills. It is probable that Dibblee's Jalama formation (6, p. 23) is of nearly the same age as these beds also. The fauna of this horizon includes specimens of a smooth giant *Pachydiscus*, P. *catarinae* and close variants; *Pachydiscus peninsularis* and close variants; *Nostoceras*-like uncoiled ammonites; and the gastropod *Cophocara stantoni*, together with a considerable and well-preserved molluscan fauna that consists largely of new species. Durham (7, p. 1537) and Kirk have suggested a probable Maestrichtean age for this fauna; Bandy (4), on the basis of foraminiferal studies, prefers a late Campanian age assignment. Indirect evidence suggests that the *Pachydiscus catarinae* beds are very close in age to the Campanian-Maestrichtean stage boundary. In terms of the California Cretaceous section, these beds probably are correlative with the Ragged Valley shale, which lies near the top of the Panoche group of the Coalinga region. Hence it seems probable that none of the Cretaceous rocks of Southern California is as young as the Moreno group of the Diablo Range, on the west side of the San Joaquin Valley.

Cretaceous strata crop out at La Jolla (10, p. 205) and at Point Loma, San Diego (9, p. 36), in exposures too small to be shown on the index map (See Hertlein and Grant, Contribution 4, Chapter II). The beds at La Jolla, mainly coarse sandstones, have yielded *Baculites*, which indicates an Upper Cretaceous age but gives little basis for a more restricted determination. The beds at Point Loma have yielded a larger number of species that have been listed by Grant and Hertlein (9), and which indicate a rather late Upper Cretaceous age for the beds. Among these are specimens of *Pachydiscus catarinae*, which, if found here in place, would correlate the Point Loma beds with the top of the Simi Hills sandstones and with the Rosario formation of Baja California. It is not yet certain, however, that the large ammonites are not reworked from a basal boulder conglomerate of the Eocene section that overlies the Cretaceous beds at the Point.

In compiling data for this report, the writer has drawn freely upon all published or unpublished sources available to him, and in regard to the Upper Cretaceous rocks he has utilized the results of much of his own unpublished research. All published sources of information that were used are included in the following list of references. In addition, the writer wishes to express his appreciation to S. W. Muller for a tentative opinion on the age of the Santa Ana Triassic beds; to E. C. Allison for free use of unpublished data on the Middle Cretaceous rocks of Baja California; and to R. W. Imlay for an opinion on the identity and age-significance of several species of Upper Cretaceous ammonites.

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4. THE MARINE CENOZOIC OF SOUTHERN CALIFORNIA[*]

By J. Wyatt Durham[†]

The marine Cenozoic of the Pacific Coast, in contrast to that in many other parts of the world, is notable for the great thicknesses of sediments accumulated locally, for rapid lateral changes in character of the sediments, and for greatly differing geological histories within short distances. These characteristic features of the Pacific Coast Cenozoic are exceptionally well developed in the part of California that lies south of the San Emigdio-Tehachapi Ranges and north of the Mexican border, which is the region considered in this paper.

On the accompanying map (fig. 1), representative areas within the region are indicated, and the southern San Joaquin Valley is included for comparison. The specific areas were chosen because the Cenozoic sequences in them are relatively well known, and because they illustrate the diversity so characteristic of the region. Formational sequences, in some instances composites, are given for these areas in figure 2. In constructing this chart, the classification based on "metazoans"—or, more familiarly, "megafossils"—used in the "Correlation of the marine Cenozoic formations of Western North America" (Weaver, et al., 1944) has been taken as a standard. This classification is based on the distribution of megafossil faunas within formations and sequences of formations, and has evolved in a rather haphazard and undisciplined manner. "Stages" based on the faunas of well known and presumably characteristic formations of different parts of the Tertiary have been recognized, but in most instances they have not been defined, nor have type sections been formally designated. The boundaries of these megafaunal stages are largely known only by inference, but nevertheless they generally have the sanctions of priority, and are used by a significant proportion of the geological profession on the Pacific Coast.

A second classification of the marine section, based on carefully disciplined studies of the distribution of foraminifera in the Pacific Coast Cenozoic, has been formulated during the last 25 years. This latter classification has been used largely by micropaleontologists, and as a result the two differing schemes have become somewhat familiarly known as the "micro" and the "mega" classifications. A third classification embodies a series of "provincial ages" and is widely used by vertebrate paleontologists in connection with terrestrial vertebrate-bearing beds. The micro and mega classifications are often applied to the same series of beds, so that their mutual relationships are fairly well understood. Only occasionally, however, do terrestrial vertebrates occur in marine beds, or do nonmarine vertebrate-bearing beds interfinger with the marine beds, and hence the relationships between the marine and vertebrate classifications are not too clear.

The relationships of the three major classifications, as now understood, are shown in figure 3 (see also Durham, et al., Contribution 7, this chapter). As can be seen from this diagram, users of these classifications do not agree very closely on the placement of the Cenozoic epoch boundaries (based on the European type sections) in the California sections (nor do they agree in all instances as to where the boundaries fall in the European sections). A consequence of this is the application of different epoch terms to the same interval, depending upon the classification used. For instance, lower Pliocene of the mammalian classification may include all of the upper Miocene of the megafaunal classification.

In the chart of figure 2, the relative vertical spaces allocated to the different megafaunal stages in the Tertiary have been determined by correlating, through the standard European section, with Simpson's (1947) "Continental Tertiary time chart," making due allowance for different interpretations of the European section in the two classifications. A proportionately larger space has arbitrarily been given the two parts of the Pleistocene. As here interpreted, but based on the time allotted by Simpson, the Paleocene included a span of about 17,000,000 years, the Eocene about 20,000,000 years, the Oligocene about 10,000,000 years, the Miocene about 19,000,000 years,

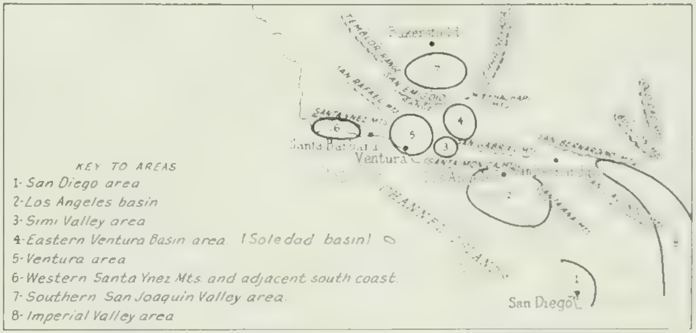

FIGURE 1. Index map of a part of southern California showing areas discussed.

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[*] Contribution from the Museum of Paleontology, University of California, Berkeley.

[†] Professor of Paleontology, University of California, Berkeley.

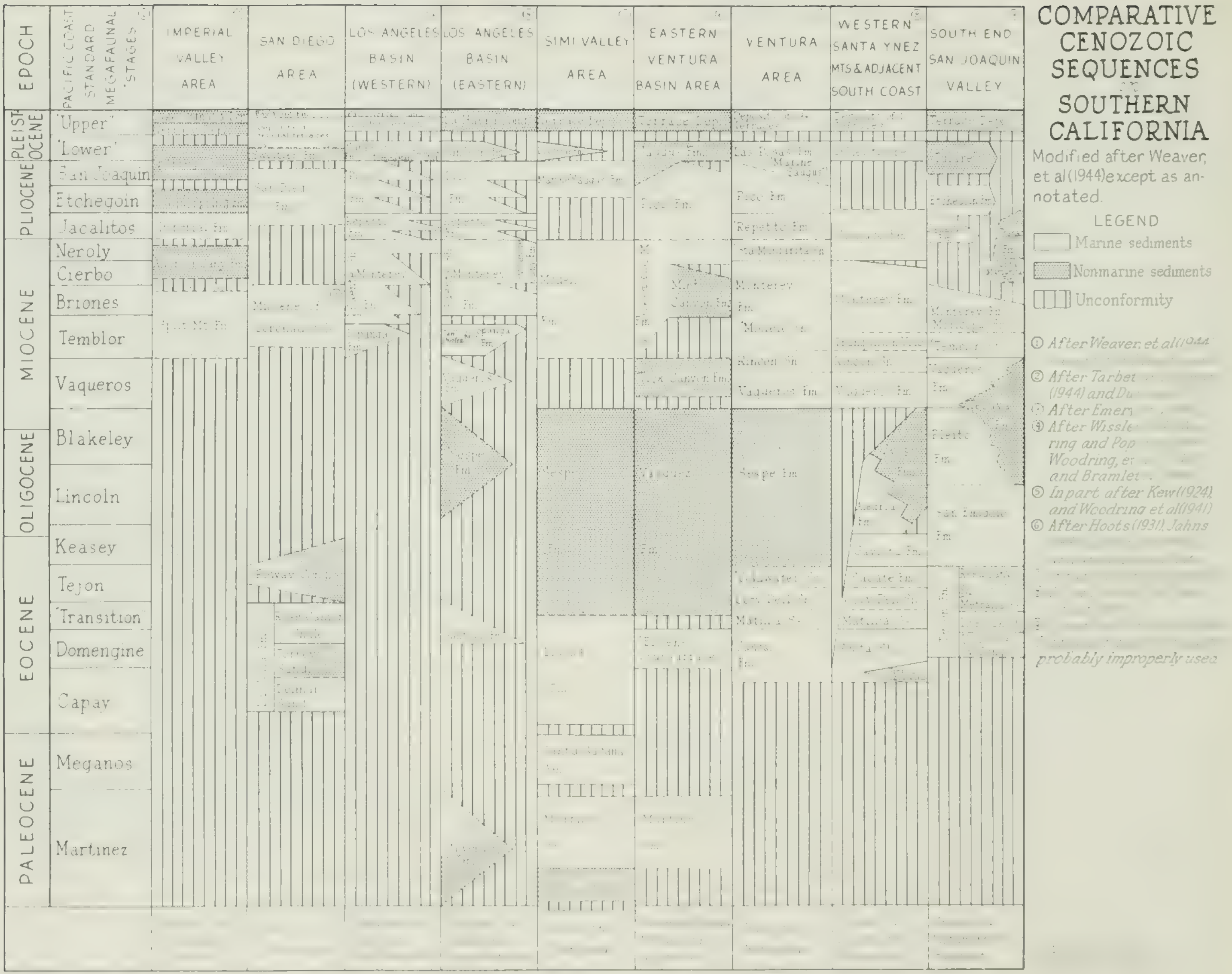

EPOCH
PACIFIC COAST STANDARD MEGAFAUNAL STAGES
IMPERIAL VALLEY AREA
SAN DIEGO AREA
LOS ANGELES BASIN (WESTERN)
LOS ANGELES BASIN (EASTERN)
SIMI VALLEY AREA
EASTERN VENTURA BASIN AREA
VENTURA AREA
WESTERN SANTA YNEZ MTS & ADJACENT SOUTH COAST
SOUTH END SAN JOAQUIN VALLEY
PLEISTOCENE
Upper
Lower
PLIOCENE
San Joaquin
Etchegoin
Jacalitos
MIOCENE
Neroly
Cierbo
Briones
Temblor
Vaqueros
OLIGOCENE
Blakeley
Lincoln
EOCENE
Keasey
Tejon
Transition
Domengine
Capay
PALEOCENE
Meganos
Martinez
Terrace Dep.
Pico Fm.
Repetto Fm.
Monterey Fm.
Rincon Fm.
Vaqueros Fm.
Sespe Fm.
Santa Susana Fm.
COMPARATIVE CENOZOIC SEQUENCES OF SOUTHERN CALIFORNIA
Modified after Weaver, et al (1944) except as annotated.
LEGEND
Marine sediments
Non-marine sediments
Unconformity
① After Weaver, et al (1944
② After Tarbet (1944) and Du
③ After Emer
④ After Wissle ring and Pop Woodring, e and Bramle
⑤ In part after Kew (1924) and Woodring et al (1941)
⑥ After Hoots (1931) Jahns
probably improperly used

FIGURE 2.

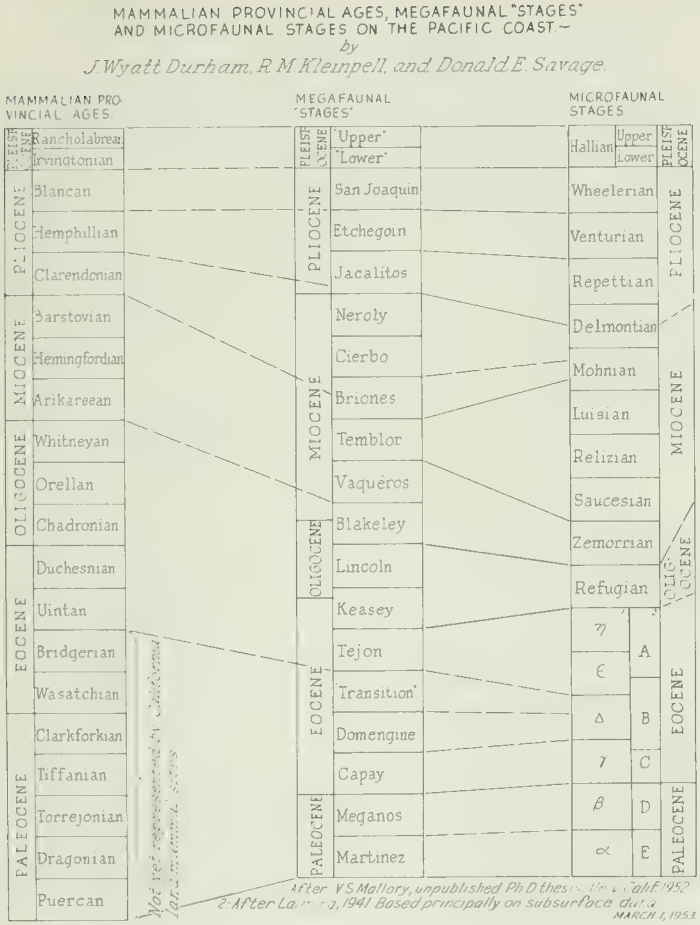
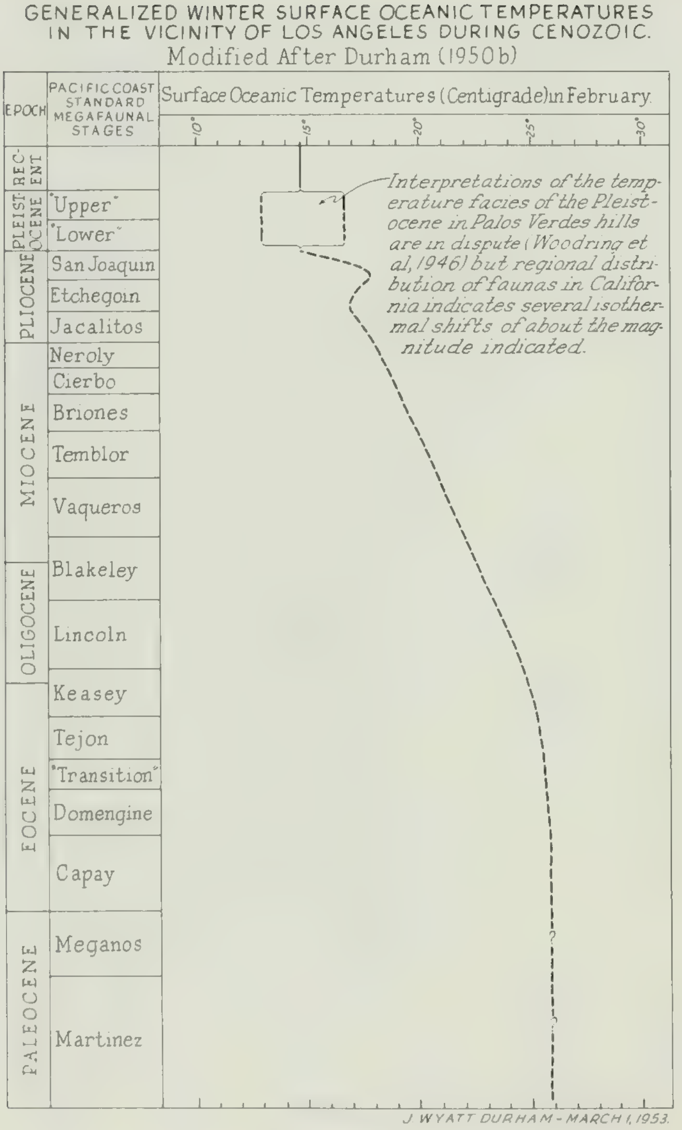


FIGURE 3.

the Pliocene about 8,000,000 years, and the Pleistocene about 1,000,000 years. As indicated by Simpson, his original figures were somewhat arbitrary but represented a consensus of opinion. The durations here assigned to the different epochs are somewhat different from those used by Simpson, but are a reflection of the different boundaries for the epochs as used in the mammalian and megafaunal classifications. The total duration of 75,000,000 years for the Cenozoic, as suggested by Simpson, is greater by about 15,000,000 years than the figure usually cited. In view of the lack of actual data on the Paleocene, Simpson considers this additional time necessary to account for the mammalian evolution that took place during this interval.

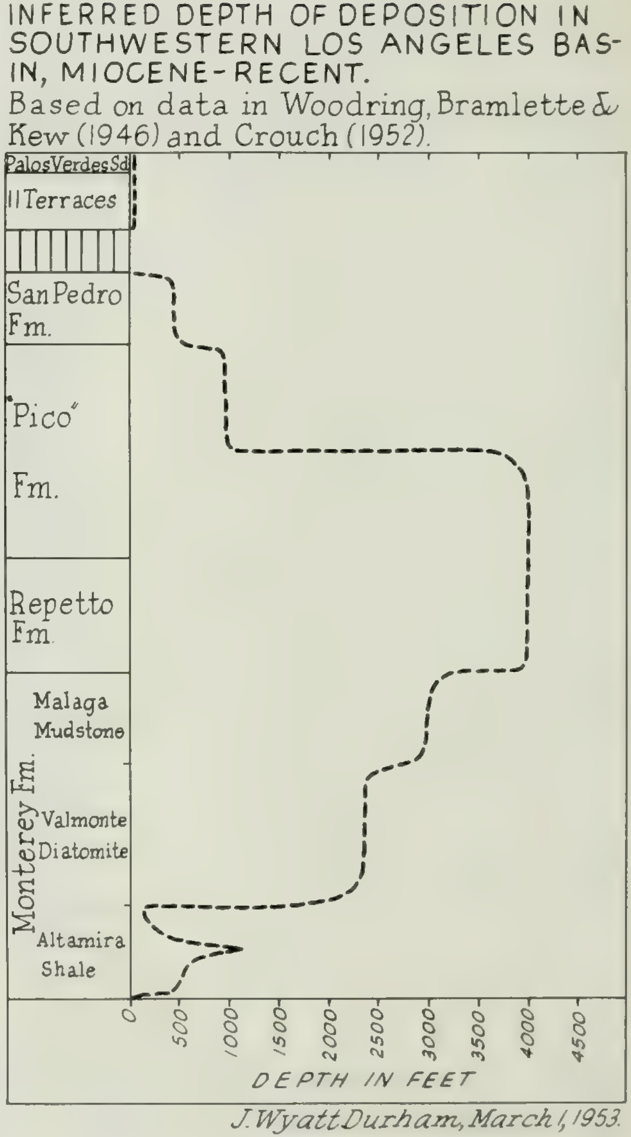
The megafaunas of the California Cenozoic show a characteristic change from the inception to the close of the era. Although they occur in latitudes comparable to those of southern Europe and North Africa, but few species are known to be common to the two regions, and the recognized indentical species are restricted to the Paleocene and Eocene. This provincialism appears to be due to the establishment of geographic and temperature barriers during the Cenozoic era, as well as to the world-wide progressive restriction of climatic belts during the Tertiary period to something approaching their present position (Durham, 1950b; 1952). The known zonal distribution of early Tertiary faunas along the Pacific Coast of the Americas also strongly militates against continental drift during the late Cretaceous or early Cenozoic (Durham, 1952). The character of the faunas suggests that the northern boundary of the tropics on the Pacific Coast during Eocene time lay north of 49° N. latitude. During the Tertiary period, the borders of the tropics gradually retreated toward the equator until they reached something approximating their present position in Pliocene time, then oscillated back and forth during the Pleistocene epoch until they attained their present position. The probable winter-time surface oceanic temperatures in the vicinity of Los Angeles during the Cenozoic era are shown in figure 4.

Imperial Valley Area. All of the areas indicated in figure 2 are within a radius of 150 miles from Los Angeles, yet within this region very differing geologic histories are represented. Sediments and faunas in the Imperial Valley area, although they crop out as close as 50 miles to sediments of similar age in the Los Angeles basin, cannot be directly compared with them because they were deposited in a former northern extension of the Gulf of California. The Gulf of California connects with the Pacific Ocean some 850 miles to the south, and in consequence has a fauna of tropical affinities whereas the faunas on the coast are warm temperate in character. Of the living molluscan fauna of the Gulf, only about 30 percent of the pelecypods and 10 percent of the gastropods occur on the Pacific Coast at San Diego (Durham, 1950a, p. 6). Similar relationships seem to have existed in the fossil faunas, and consequently age assignments in the Imperial Valley area comparable to those of the


GENERALIZED WINTER SURFACE OCEANIC TEMPERATURES IN THE VICINITY OF LOS ANGELES DURING CENOZOIC.
Modified After Durham (1950b)

J WYATT DURHAM - MARCH 1, 1953.

FIGURE 4.


INFERRED DEPTH OF DEPOSITION IN SOUTHWESTERN LOS ANGELES BASIN, MIOCENE-RECENT.
Based on data in Woodring, Bramlette & Kew (1946) and Crouch (1952).

J. Wyatt Durham, March 1, 1953.

FIGURE 5.

coastal areas have been very difficult to make. The most fossiliferous and best known marine formation, the Imperial, has been variously assigned Cretaceous, lower Miocene, middle Miocene, upper Miocene, and Pliocene ages. On the basis of data discussed elsewhere (Durham, 1950a, pp. 23-25, 28-33), the Imperial formation and its equivalents are here considered to be of early Pliocene age.

According to available information, there appears to be a minimum of about 14,000 feet and a possible maximum of more than 20,000 feet of sediments in the Imperial Valley area. Despite this thick section, the oldest formation (Split Mountain) does not appear to be older than about middle Miocene, and the major part of the sediments are of Pliocene age and are mostly nonmarine. Little literature is available on the Cenozoic rocks of the area. Tarbet and Holman (1944) and Durham (1950a) have considered the area during recent years, and Durham's paper contains a bibliography of earlier papers. Wilson's (1948) contribution on the Santa Rosalia area, Baja California, contains much valuable information bearing on the history of the Gulf of California. The general geology of the Imperial Valley area is discussed by Dibblee in Contribution 2, Chapter II, this volume.

San Diego Area. The San Diego area is a part of the Pacific coastal province in which only local limited marine embayments have been present during the Eocene, Pliocene, and Pleistocene epochs. Marine Miocene has been reported (Emery, et al., 1952) from the Coronados Islands, a short distance offshore, but has not been found on the mainland. The Eocene sediments and faunas are discussed by Hanna (1927), and Hertlein and Grant (1944) have described the Pliocene and Pleistocene geology of the area (see also Contribution 4, Chapter II). In accordance with the position along an open coast, without much drainage from adjacent inland areas, the Cenozoic sediments of the San Diego area are comparatively thin, and comprise about 1,600 feet of Eocene, 1,250 feet of Pliocene, and perhaps 200 feet of Pleistocene beds. The Miocene rocks of the Coronados Islands may be more than 700 feet thick. These sections are considerably thinner than in most other areas to the north, but appear to be similar to those that occur farther south along the coast of Baja California. It would appear that during Cenozoic time the shoreline in the San Diego area oscillated back and forth from a position essentially similar to the present one.

Los Angeles Basin. The Los Angeles basin is a more or less rectangular area of low relief, and is about 25 by 50 miles in major dimensions. It is mainly surrounded by hills and mountains in which most of the subsurface formations crop out. Because of the early discovery of petroleum in this area the basin has been intensively studied, particularly in the subsurface, and consequently a great deal is known about the Miocene and Pliocene sections, which contain the principal oil-producing horizons. Important papers dealing with the area or with parts of it include those of Dickerson (1914a); Driver (1948); Grant and Gale (1931); Hoots (1931); Loel and Corey (1932); Wissler (1943); Woodring (1938); Woodring and Popenoe (1945); and Woodring, Bramlette, and Kew (1946).

Driver (1948) and others have indicated that the Los Angeles basin is composed of a number of structural blocks that have acted independently of one another, with the consequence that the stratigraphy of these different blocks may differ considerably. Stratigraphic sequences for both the eastern and western parts of the basin (including the adjacent hills) are presented in figure 2, in order to show this diversity of their Cenozoic history. The total maximum possible thickness of Cenozoic sediments in the Los Angeles basin and adjacent hills appears to be of the order of 40,000 feet, but within much of the basin proper the thickness appears to be of the order of 20,000 feet. Nearly 15,000 feet of sediments have been penetrated in a single well.

Within the basin most of the sediments are of middle and upper Miocene and Pliocene ages, and the greatest thicknesses are in the synclines between the major structural trends. Unconformities commonly are developed on the flanks of the structural highs. The Paleocene, Eocene, Oligocene, and lower Miocene formations are found only in local areas, mostly around the margins of the basin, but the available evidence would seem to indicate that Paleocene and lower Miocene seaways covered most of the region. During Oligocene time it seems that only nonmarine sedimentation or nondeposition occurred through most of southern California. The basement complex has been reached by wells in a number of fields on the west side of the basin, where it lies beneath middle Miocene rocks. This indicates that the older Tertiary rocks, if ever present here, had been removed by erosion, at least over the structural highs, prior to middle Miocene time.

In the southeastern corner of the basin is the San Onofre breccia (Woodford, 1925), a locally very coarse deposit that is composed of angular slabs and boulders of schistose rocks derived from an offshore western source. This material is interbedded with marine middle Miocene sediments, and gives striking evidence of one of the Tertiary paleogeographic changes that took place in the region.

According to data presented by Natland (1933, subsequently modified by Crouch), Woodring (1938, pp. 12-18), Woodring, Bramlette, and Kew (1946, pp. 39-40, 42, 86-96), and Crouch (1952), the upper Cenozoic of this area includes sediments that were laid down at depths much greater than those commonly considered as probable for deposition within the continental margins. The probable depths of deposition of sediments in the southwestern part of the basin, based on data presented by the above authors, are shown in figure 5.

Woodring, Bramlette, and Kew (1946) have recorded 12 marine terraces of upper Pleistocene age, extending up to an elevation of 1,215 feet above sea level, from the Palos Verdes hills in the southwestern part of the Los Angeles basin. One of the outstanding features of the coastal Pleistocene is the occurrence of these marine terraces from this area northwestward along the coast to Point Conception (if not farther), and yet not extending far inland.

Cajon Pass Area. Woodring (1942) has recorded lower Miocene (Vaqueros) marine fossils from the Cajon Pass area, some 45 miles northeast of Los Angeles. The containing sediments are involved in the San Andreas fault zone, and are not known to be connected to any of the more coastal outcrop areas of this formation. Unless there has been many miles of lateral movement along the fault, the isolated position of these marine sediments is difficult to explain (see Noble, Contribution 5, Chapter IV).

Simi Valley Area. The Simi Valley area is only 30 miles northwest of the center of Los Angeles, and yet it is on the opposite side of the Santa Monica Mountains and represents a different depositional basin. It is situated on the south side of the major east-trending Ventura basin, and contains the most complete lower Tertiary succession known within the basin. Pertinent literature on the Simi Valley section includes contributions by Grant and Gale (1931), Hoots (1931), Kew (1924, 1943), Laiming (1941), Nelson (1925), and Stipp (1943).

The maximum possible thickness of Cenozoic rocks in the Simi Valley area appears to be of the order of 15,000 feet, and some 6,200 feet of this comprises beds of Paleocene and lower to middle Eocene ages. This is the best developed Paleocene-lower Eocene sequence in the southern part of the State. The overlying nonmarine Sespe formation of upper Eocene to lower Miocene age may be as much as 5,000 feet thick. The marine Vaqueros and Topanga formations may overlie the Sespe in areas immediately adjacent to, but not within the restricted area from which the present section is taken. Kew (1924) and Hoots (1931) treat these formations in considerable detail. The upper Miocene Modelo formation is strongly transgressive on older formations, and the upper Pliocene section is marine here instead of continental as it is a short distance to the northeast.

Ventura Basin. The eastern Ventura basin area includes the Soledad basin,* in the easternmost part of the area, where marine and nonmarine beds interfinger and where marginal orogenic movements have created unconformities that are not present throughout the region. The papers of Dehlinger (1952), Dickerson (1914b), English (1914), Grant and Gale (1931), Hoots (1931), Jahns (1940), and Kew (1924, 1943) contain many data and many descriptions of fossils pertinent to the area. The area is critical also for the light it sheds on the relationships of the later Tertiary marine and continental (mammalian) time scales of the Pacific Coast (see Durham, et al., Contribution 7, this chapter).

The Paleocene "Martinez" formation is widely but erratically distributed throughout this area, as well as eastward to the San Andreas fault zone along the western margin of the Mojave Desert (Dickerson, 1914b). It also is structurally involved in the San Gabriel Mountains, and occurs in the hills along the northern margin of the Ventura basin. Middle Eocene sediments are known from wells only, and are at least 1,500 feet thick. In the northeastern part of the area, the nonmarine Vasquez formation is approximately 9,000 feet thick, and is interlayered with an additional 4,000 feet of andesitic and basaltic flows and concordant intrusives. The Vasquez sediments apparently were deposited in local fault-block basins, and presumably are the local equivalent of the Sespe formation. They are overlain with marked unconformity by the nonmarine Tick Canyon formation, which in turn is unconformably overlain by the nonmarine Mint Canyon formation. A well-marked unconformity separates the Mint Canyon beds from the overlying marine Modelo (?) formation in the Soledad basin. The post-Vasquez formations have a total thickness of about 5,300 feet, of which about 4,700 feet is nonmarine.

The marine Modelo (?) formation contains a fauna of upper Miocene (Cierbo and Neroly) age (Jahns, 1940, pp. 166-167; Durham, 1948) in terms of the marine section, whereas the underlying Mint Canyon formation contains a vertebrate fauna of late Clarendonian age (late lower Pliocene) in terms of the terrestrial vertebrate section. These discrepancies have given rise to much discussion and speculation, but are part of a much larger problem discussed elsewhere in this chapter (Durham, et al., Contribution 7). Suffice it to say here that the upper Miocene of the marine sections is at least in part the equivalent of some of the lower Pliocene of the terrestrial mammalian sequence.

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* To avoid confusion, the name Soledad basin has been given to the easternmost part of the Ventura basin that lies east of the San Gabriel fault (Bailey and Jahns, Contribution 6, Chapter II, this volume).

To the southwest and west of the Soledad basin these nonmarine formations do not crop out, and instead a conformable sequence of marine sediments, all referred to the Modelo formation, is apparently the equivalent of the combined Modelo (?) and Mint Canyon formations, together with the intervening unconformity, of the Soledad basin. One possible explanation of the discrepancies may be that the San Gabriel fault (Kew, 1924, pl. 8), a major lateral break that trends northwest, may separate areas with differing geologic histories during the Miocene (see Crowell, Contribution 6, Chapter IV), but Kew's (1943, p. 412) record of Mint Canyon strata underneath marine Modelo beds in wells near Newhall south of the San Gabriel fault argues against this hypothesis.

The nonmarine Saugus formation, which unconformably overlies the lower and middle Pliocene Pico formation in this area, becomes marine toward the west and forms part of a very thick, apparently conformable Pliocene-lower Pleistocene sequence in the more western areas.

The Ventura area is on the north flank and about midway between the ends of the east-trending Ventura basin, and is situated where the western portion (except the north flank) of the basin extends beneath the sea (Santa Barbara channel). The area also includes an extremely thick (about 18,000 feet) Pliocene-lower Pleistocene section that has yielded much oil. Reed and Hollister (1936, p. 102, fig. 39) have indicated that the Cenozoic section in this area is nearly 50,000 feet thick, and that the total post-Jurassic sedimentary blanket here is about 68,000 feet thick. The literature on the area includes important papers by Bailey (1935); Bramlette (1946); Cushman and Laiming (1931); Grant and Gale (1931); Loel and Corey (1932); Natland (1933); Natland and Kuenen (1951); Pressler (1929); Putnam (1942); Reed and Hollister (1936); Stewart (1943); and Waterfall (1929).

In accordance with the great thickness of sediments and their presumed position near the middle of the geosyncline, the section is largely concordant (except possibly along the flanks of the embayment), even though the Sespe formation is nonmarine. A few miles to the east the Sespe beds lie unconformably on Eocene beds. The middle and upper Miocene Monterey formation, composed of predominantly siliceous rocks locally known as the Modelo formation, is characterized by striking local changes in thickness in an east-west direction in the Ventura basin. Equivalent beds in the area east of Ventura range in thickness from about 1,000 feet to 7,000 feet in a distance of 10 miles (Bramlette, 1946, pp. 708, pl. 2).

Great interest is attached to the Pliocene-Pleistocene units of this area because of their thickness and because of the depth of deposition indicated by their faunas. Larger fossils are scarce except in obviously shallow-water intervals near the top of the sequence, but Foraminifera are abundant, particularly in the lower part. Natland (Natland and Kuenen, 1951, pp. 79-85, fig. 2) has concluded, on the basis of the Foraminifera present, that in lower Pliocene time the center of the basin was 4,000 to 5,000 feet deep, and that the basin gradually became shallower up to the middle Pleistocene. Natland and Kuenen describe many sedimentary features that they consider characteristic of deeper water deposition. Within the Pleistocene beds, marked lateral changes in fauna have been noted (Bailey, 1935). The upper Pleistocene is represented here, as in the western Los Angeles basin, by at least nine terraces along the coast (Putnam, 1942). The highest of these lies at altitudes of as much as 1,300 feet.

Western Santa Ynez Mountains and Adjacent Coastal Area. The western Santa Ynez Mountains and the adjacent south coast area also are situated along the north flank of the Ventura basin, but are some 50 miles west of the Ventura area. The section is very similar to that of the Ventura area, except that it is much thinner and all of the formations become marine in the western part of the area. An extensive report on this part of the basin has recently been published (Dibblee, 1950), and Upson (1951) has discussed the numerous upper Pleistocene marine shorelines developed along the south flank of the mountains. According to Dibblee, the maximum probable thickness of Cenozoic sediments in the area is about 20,000 feet, or less than half that found around Ventura. In the northwestern part of the area there is a well developed unconformity at the base of the Vaqueros formation, a feature not found in the more eastern areas. The Alegria and Gaviota formations, the westernmost equivalents of the nonmarine Sespe of the Ventura region, are marine and contain faunas not found elsewhere in the southern part of the State.

Seventeen upper Pleistocene marine shorelines, the highest of which extends to a maximum elevation of about 1,660 feet above sea level, are recorded by Upson, indicating that the upper Pleistocene history of this area was similar to that of the Ventura area and the western Los Angeles basin area. One of the notable Pleistocene problems of southern California is an explanation of these terraces and why they do not extend far inland from the coastline.

Southern San Joaquin Valley. A column for the southern San Joaquin Valley area is included in figure 2 for comparison, as it is characteristic of the areas that lie north of a presumed Cenozoic barrier along the north flank of the Ventura basin. The data in the column were derived in large part from the work of Hoots (1930).

Further discussion of this area appears in Contribution No. 8, Chapter II.

Other Areas. In the preceding discussion and in the correlation chart, no mention or indication is made of the Santa Monica Mountains, the north side of the Ventura basin east of Santa Paula, the offshore Channel Islands area, and other locally significant areas, because of the space limitations in the present volume. Interested readers may refer to Reed's (1933) excellent summary volume, or to Hoots (1931) for coverage of the Santa Monica Mountains. A very interesting problem, discussed by Bramlette (1946), is the origin of the marine sedimentary siliceous rocks (diatomites, porcelanites, chert, siliceous shales, etc.) of the widespread Monterey formation, of Miocene age. Numerous other interesting and significant features and problems also are present, but space limitations do not permit mention or discussion of them.

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5. FOSSIL FORAMINIFERA OF THE LOS ANGELES AND VENTURA REGIONS, CALIFORNIA

By M. L. Natland[*] and W. T. Rothwell, Jr.[†]

Foraminifera are very abundant through the Cenozoic and Upper Cretaceous strata of the Los Angeles and Ventura basins. An index map to collecting localities is presented in figure 1, and characteristic species are illustrated in figure 2. "Forams" are the principal tool by which petroleum geologists in southern California correlate strata. After well sections or outcrops have been classified in terms of age, the foraminiferal yardstick is applied to surface mapping, electric-log correlations, and geophysical data. Figures 6 and 7 show thickness, principal rock types (1),[1] and guide fossils (3) in the Cenozoic, which overlies—generally with profound unconformity (2)—Upper Cretaceous sediments or pre-Upper Cretaceous metamorphic and igneous rocks.

Cretaceous. Figure 3E shows collecting localities in rocks of Upper Cretaceous age (7) in Silverado Canyon, Santa Ana Mountains. The Holz member of the Ladd (6) formation contains Foraminifera that correlate with the Taylor in Texas. The microfauna of the Upper Cretaceous in southern California (8, 10) is not well known, in comparison with those of other strata, owing to the lack of petroleum development. *Globotruncana arca* and *Anomalina henbesti* are characteristic forms in the Ventura basin, in the Santa Ana Mountains, and in San Diego County (10). They correlate with the Panoche group of the San Joaquin Valley (9), with the Campanian, and possibly, in part, with the Maestrichtian of Europe.

Paleocene. In figure 4B, in the Santa Susana formation (11), in Simi Valley localities 1091 and 1098 of Cushman and McMasters (21), and at R.S. 53 and R.M. 51 are found excellent specimens of such Paleocene foraminifers (13) as *Bolivina applini* and *Globorotalia velascoensis*, age equivalents of Mountain and Danian European stages, the Velasco shale (12) of the Tampico embayment, and Midway of Texas.

Eocene. Figure 4A shows location of well-exposed upper Eocene Coldwater, Cozy Dell, Matilija, and "Juncal" formations along U. S. Highway 399 north and northwest of Ojai. The Cozy Dell shale yields an abundant microfauna, "A" zone of Laiming (13), characterized by *Plectofrondicularia jenkinsi*, *Cibicides cushmani*, and *Asterigerina crassiformis*. These formations span the Bartonian and Auversian stages (3). Localities 1095 and 1096 (fig. 4B) of Cushman and McMasters (21) expose a sequence of the early upper, middle, and lower Eocene Llajas formation containing *Discocyclina cloptoni* (18), *D.* cf. *psila*, *D. Clarki*, and *Amphistegina semiensis*. The Llajas formation (22) is equivalent in age to the Sierra Blanca limestone (19), Anita formation (24), and "Juncal" formation of the Santa Ynez Mountains, and to the Domengine, Capay, and upper part of the Meganos in the central California Coast Ranges (3). The Llajas formation is approximately the age of the Auversian (in part), Lutetian, Cuisian, and Ypresian European stages (3).

Oligocene. Lower and middle Oligocene time in southern California is represented by the Sespe formation of terrigenous facies. The marine representatives of the Refugian (28) and lower Zemorrian stages of central California are missing. These equal the Ludian, Tongrian, and early Rupelian European stages (3). The marine

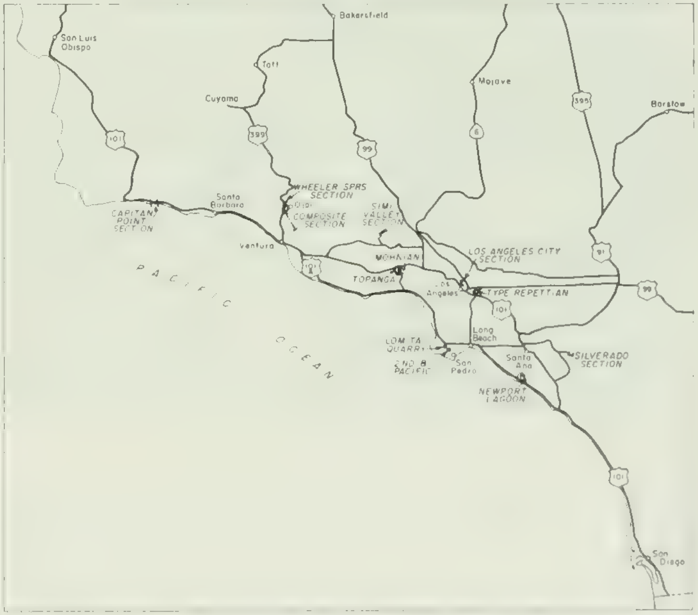

Figure 1. Index map of a part of southern California, showing collecting localities for fossil Foraminifera.

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[1] Figures in parentheses refer to references at the end of this paper.

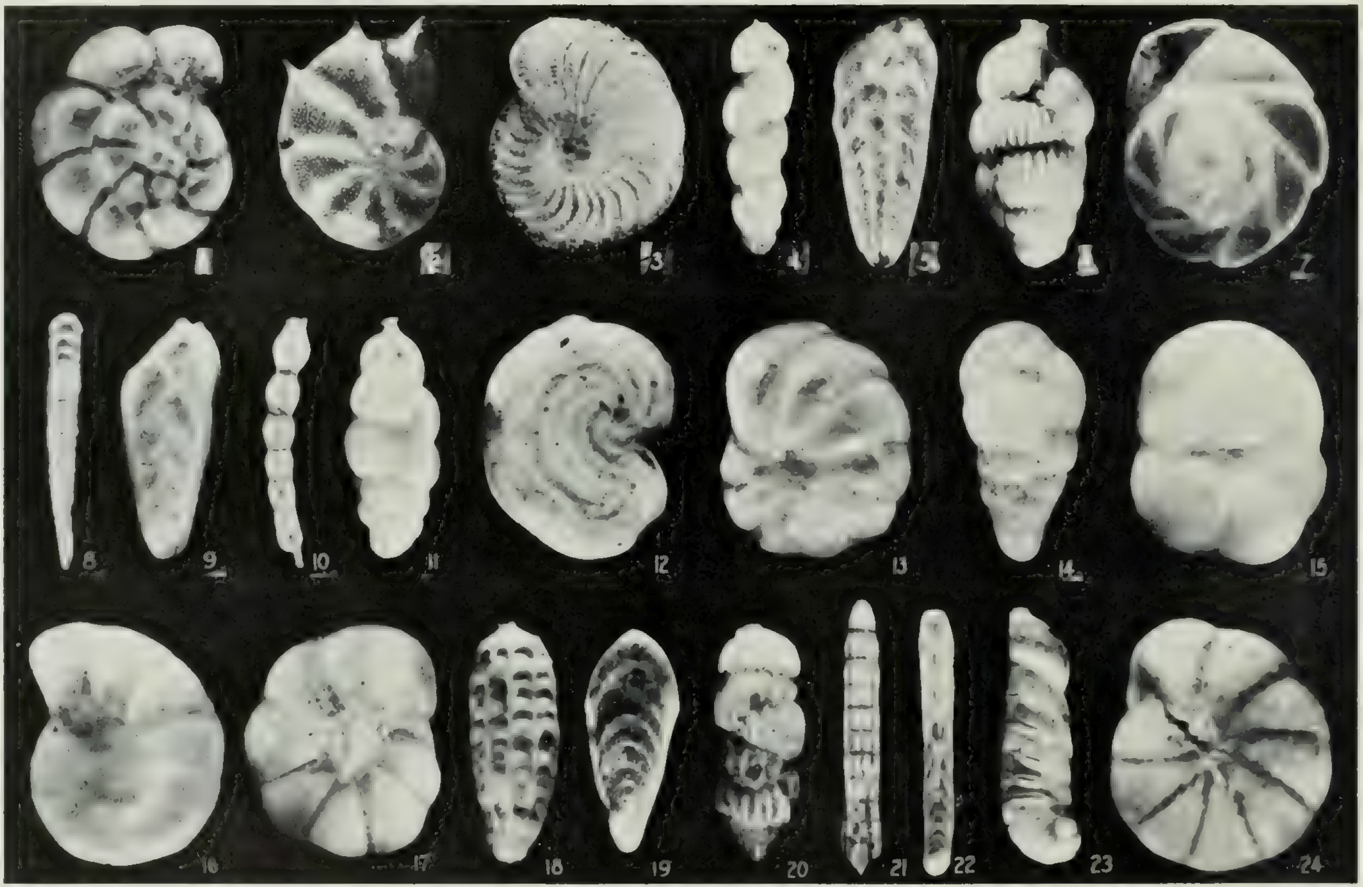

FIGURE 2. Tertiary foraminiferal guide fossils. 1. *Rotalia beccarii* Linné, Pleistocene, Hallian stage. 2. *Elphidium spinatum* Cushman & Valentine, Pleistocene, Hallian stage. 3. *Elphidium* cf. *Crispum* (Linné), Pleistocene, Hallian stage; and upper Pliocene, Wheelerian stage. 4. *Uvigerina juncea* Cushman & Todd, lower Pleistocene, Hallian stage; and upper Pliocene, Wheelerian stage. 5. *Bolivina interjuncta* Cushman, upper Pliocene, Wheelerian stage. 6. *Uvigerina striata* d'Orbigny var. *"attenuata"* Coryell & Mossman (non Cushman & Renz), upper Pliocene, Wheelerian stage. 7. *Epistominella Pacifica* (Cushman), Pliocene and upper Miocene. 8. *Plectofrondicularia californica* Cushman & Stewart, lower Pliocene, Repettian stage. 9. *Bolivinita angelina* Church, middle lower Pliocene, Repettian stage. 10. *Siphonodosaria verneuili* (d'Orbigny), lower Pliocene, Lower Repettian stage. 11. *Uvigerina hootsi* Rankin, M. S., upper Miocene, Mohnian and Delmontian stages. 12. *Cassidulinella renulinaformis* Natland, upper Miocene, Upper Mohnian stage. 13. *Epistominella gyroidinaformis* (Cushman & Goudkoff), early upper Miocene, Lower Mohnian stage. 14. *Bulimina uvigerinaformis* Cushman & Kleinpell, early upper Miocene, Lower Mohnian stage. 15. *Baggina californica* Cushman, early upper and late middle Miocene, Lower Mohnian and Luisian stages. 16. *Anomalina salinasensis* Kleinpell, middle Miocene, Luisian stage. 17. *Valvulineria californica* Cushman, middle Miocene, Luisian stage. 18. *Siphogenerina transversa* Cushman, lower Miocene or upper Oligocene, Saucesian stage. 19. *Plectofrondicularia miocenica* Cushman, lower Miocene and upper Oligocene, Lower Relizian, Sauceisan, and Zemorrian stages. 20. *Siphogenerina mayi* Cushman & Parker, lower Miocene and upper Oligocene, Lower Saucesian and Upper Zemorrian stages. 21. *Nodosaria latejugata* Gumbel, Eocene. 22. *Amphimorphina jenkinsi* (Church), upper Eocene, A-1 zone of Laiming. 23. *Vaginulinopsis saundersi* (Hanna & Hanna) Beck, Eocene. 24. *Eponides guayabalensis* Cole, Eocene and Paleocene.

Vaqueros (25) sand and shale conformably overlying the Sespe "red-beds" has been assigned to the upper Zemorrian stage, *Uvigerinella sparcicostata* zone, by R. M. Kleinpell (34). He correlates the Zemorrian stage with the Rupelian stage, middle or upper Oligocene of Europe. Important members of the upper Zemorrian stage, Vaqueros formation fauna, of the Ventura basin are *Valvulineria casitasensis* and *Siphogenerina nodifera*. Glaessner (46) states that most authors place the Rupelian of Europe in the upper Oligocene. R. M. Kleinpell's upper Zemorrian-stage Vaqueros formation (restricted) in California would approximate the Rupelian of Europe. "Oligo-Miocene" Chattian and Aquitanian stages of Europe are equivalent to the Saucesian (34) stage of the Ventura and Santa Barbara coastal regions. Such forms (32) as *Siphogenerina transversa*, *Plectofrondicularia miocenica*, *Cibicides americanus*, and *C. floridanus* are abundant in the Saucesian-stage Rincon formation, located on figure 4C, where it underlies the Obispo tuff and crops out in the sea cliff east of Capitan Point, Santa Barbara County.

Miocene. Figure 4C shows the location of a complete Miocene section in the sea cliff westward from the "Oligo-Miocene" Rincon formation near Capitan Point. Collecting localities are almost continuous, stratigraphically upward, in diatomaceous shales through the Relizian, Luisian, and Mohnian stages, and into Delmontian stages of the Monterey formation. These stages of Kleinpell represent, in the same order, time equivalents of the Burdigalian, Helvetian, Tortonian, and Sarmatian stages of Europe.

The Relizian stage at Capitan Beach (fig. 4C) contains *Siphogenerina branneri* and *Baggina robusta*. This stage is represented in the Los Angeles basin by the littoral-facies strata of the lower part of the type Topanga formation (fig. 4D) containing *Pecten nevadanus* and *Turritella temblorensis*, along with shallow neritic nonions and ostracodes.

The Luisian-age strata at Capitan Beach consist of soft foraminiferal shales and hard, white limestones containing *Siphogenerina collomi* and *Valvulineria californica*. This stage also is represented 150 miles to the southeast, at Newport lagoon in Orange County (fig. 3C), by a white, diatomaceous, laminated shale with the same guide fossils. The Newport locality is easily accessible from Highway 101 (Alternate), 30 miles south of Los Angeles.

Collecting localities for the Mohnian stage of the upper Miocene can be easily reached at Capitan Beach (fig. 4C), at Newport (fig. 3C), at the locality of the type Mohnian stage of R. M. Kleinpell, mapped by H. W. Hoots (5) (fig. 4E), and in the City of Los Angeles (fig. 5). Similar faunas are encountered at all four localities. Type Mohnian strata overlie the sandstone and volcanic rocks of the lower Topanga formation (Relizian).

Along Topanga Canyon Avenue (fig. 4E), proceeding northward from the contact with the subjacent Topanga locality, the beds at locality R 38 contain the lower Mohnian species *Epistominella ("Pulvinulinella") gyroidinaformis*, *Bulimina uvigerinaformis*, and *Baggina californica*. Near the summit of the Santa Monica Mountains, upper Mohnian *Bolivina hughesi* and *Discorbinella valmonteensis* can be collected at locality H 130. At locality H 144, *Cassidulinella renulinaformis* (36) can be seen on bedding planes. Locality H 174, near Ventura Boulevard (Hwy. 101), has a meager upper Miocene Delmontian-stage fauna with *Cassidulina delicata* in soft, laminated diatomite. The contact with the overlying Pliocene is not exposed. The same upper Miocene sequence is intermittently exposed in the City of Los Angeles, north of the Statler Hotel (fig. 5).

The Delmontian stage (Sarmatian-early Pontian of Europe) is represented by deep-water facies in the Los Angeles basin (34, 38), in contrast to other areas in California. It is characterized by massive, silty lithology and an abundance of Radiolaria, and is a major oil producer in southern California. The fauna is similar to the lower Pliocene, but with the addition of its guide fossil *Rotalia garveyensis*. Figure 5 shows outcrops in Los Angeles.

Pliocene. Graphic representations of Pliocene history in the Los Angeles and Ventura basins are shown on figures 6 and 7. The most complete early Pliocene section exposed in the Los Angeles region is in the Repetto Hills of eastern Los Angeles (fig. 3D), which M. L. Natland (54) has designated the type representative of the Repettian stage of the lower Pliocene. Repettian foraminifers may be collected also in the Palos Verdes Hills (43), along Narbonne Avenue (fig. 3A), and in central Los Angeles City, near the Statler Hotel (fig. 5). In most surface exposures surrounding the Los Angeles basin, beds of the Repettian are overlain by beds that represent Natland's (54) Wheelerian stage (upper Pliocene). Thus, a Venturian-stage fauna (middle Pliocene) generally is missing on the margin of the basin, although it is well represented by such forms as *Bulimina subacuminata* in the oil-well sections of the central basin (38).

Figure 7 shows biostratigraphic and lithologic divisions of the Ventura basin, with the Pliocene stage names proposed by M. L. Natland (53, 54). Type localities for the Venturian and Wheelerian stages are located on a ridge paralleling the east side of Wheeler Canyon, Ventura County, approximately 4 miles west of the City of Santa Paula. Easily accessible beds that are representative of these stages, as well as strata correlative with the type Repettian section in Los Angeles, are exposed along Santa Paula Creek, north of the city. Guide fossils are listed on figure 7.

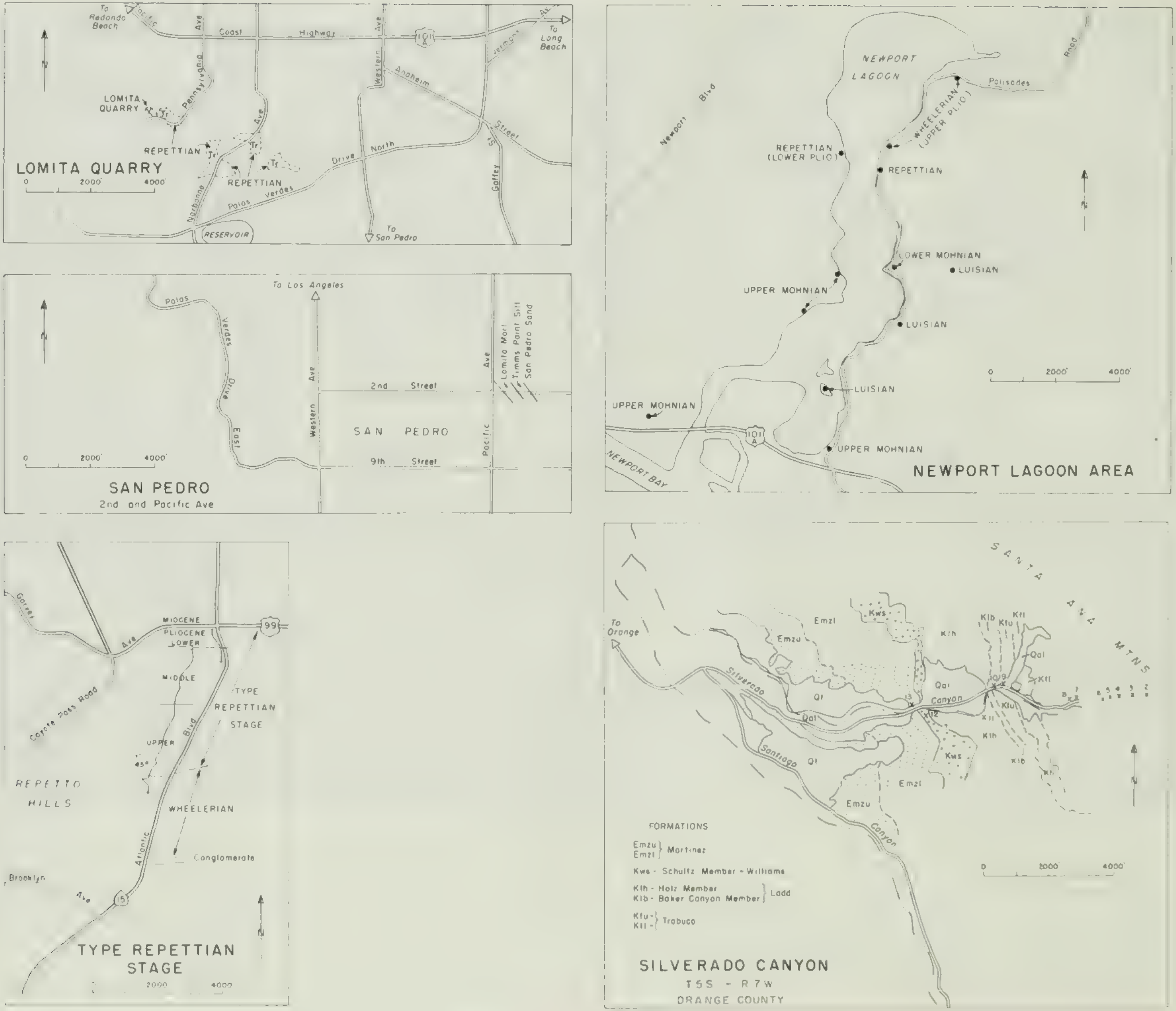

FIGURE 3. Foraminiferal sections.

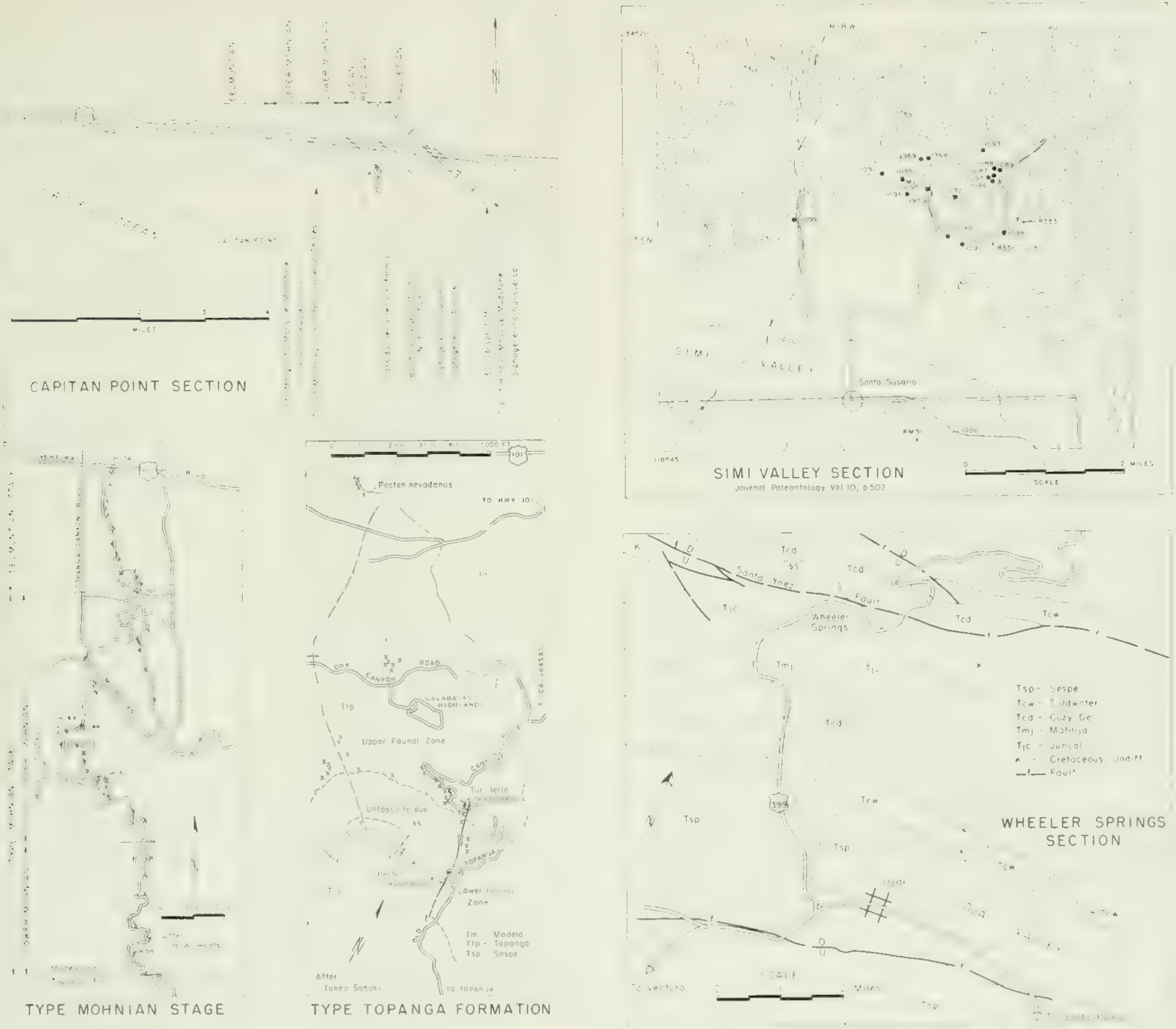

FIGURE 4. Foraminiferal sections.

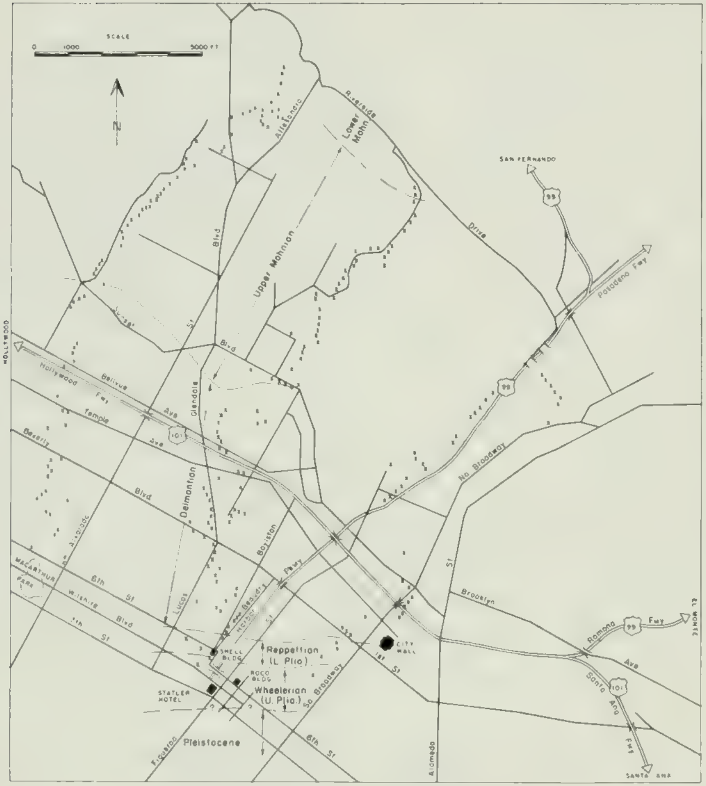

FIGURE 5. Los Angeles City sections.

A composite section (fig. 6) from Signal Hill (Long Beach oil field wells) shows Miocene and Pliocene stages and their guide fossils. Upper Pliocene Wheelerian strata (52) can be sampled in Los Angeles near the Statler Hotel (fig. 5). Beds of this stage unconformably overlie the type Repettian (54) west of Atlantic Boulevard in Los Angeles (fig. 3D), and also appear at Newport lagoon (fig. 3C).

Pleistocene. An easily accessible and completely exposed section in Hall Canyon (49, 51), northeast of the City of Ventura, has been described by M. L. Natland (53, 54) as the type locality for the lower Pleistocene Hallian stage overlying the upper Pliocene Wheelerian stage. The Hallian stage is characterized by a *Cassidulina limbata* fauna, ranging through the upper half of Bailey's (58) Santa Barbara formation. Overlying the Hallian in Hall Canyon are several thousand feet of marine beds deposited in a shallow neritic environment, and these in turn are overlain by terrigenous deposits that have been variously classified as lower or upper Pleistocene (61).

Lomita Quarry (fig. 3A) affords a well-exposed outcrop of Hallian-stage (early Pleistocene) Lomita marl. This is the locality from which Galloway and Wissler (57) described a large fauna. Many forms here, such as *Bolivina sinuata*, *Cassidulina lomitensis*, and *Cibicides mckannai*, are believed to be reworked from the immediately underlying Repettian beds. Characteristic species at Lomita Quarry are *Cassidulina limbata* and *C. tortuosa*. Figure 3D shows collecting localities in the City of San Pedro. Numerous species of Ostracoda described by L. W. LeRoy (59) are found both at Lomita Quarry and in San Pedro.

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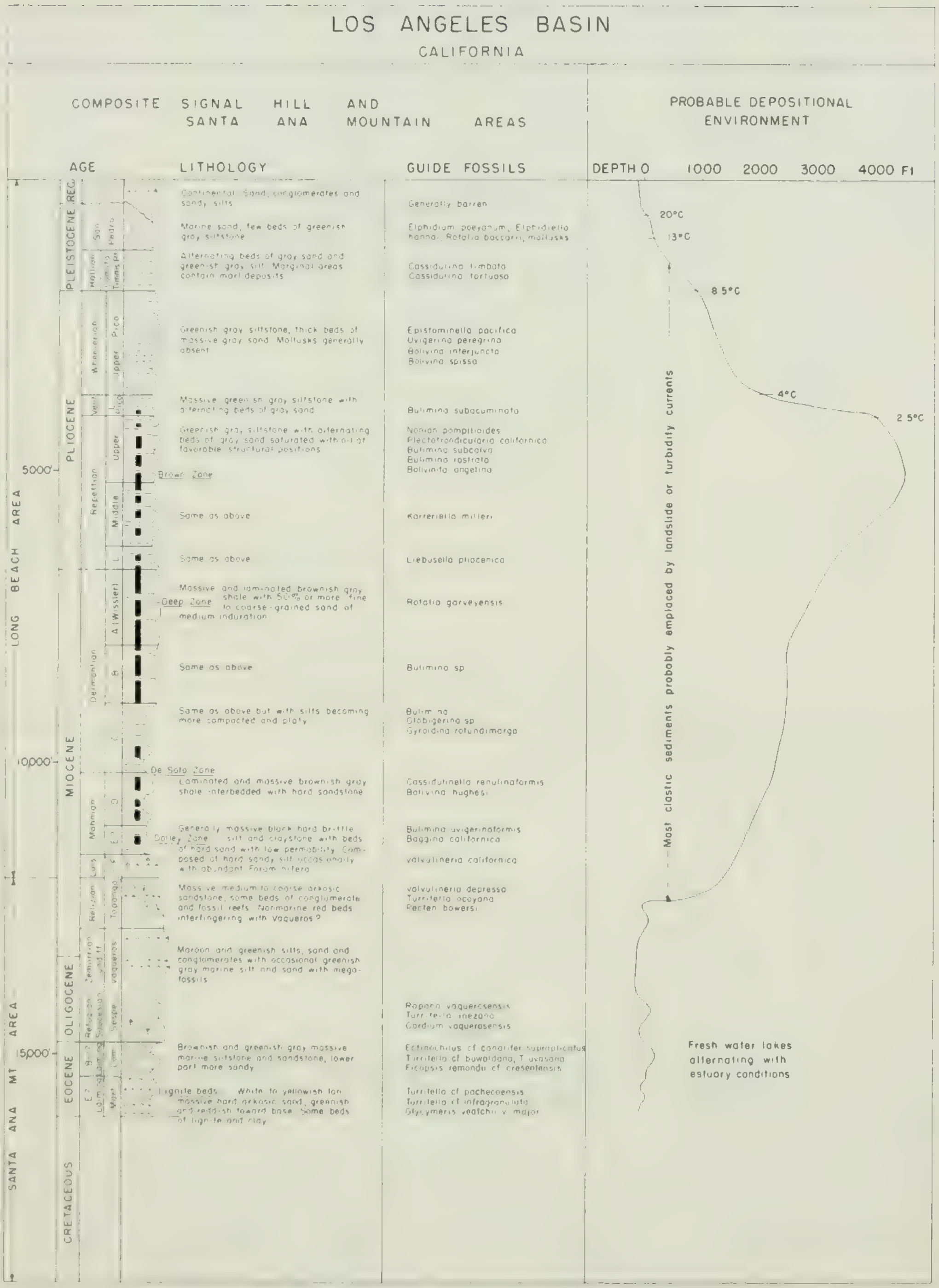

FIGURE 6. Composite section and foraminiferal guide fossils, Los Angeles basin.

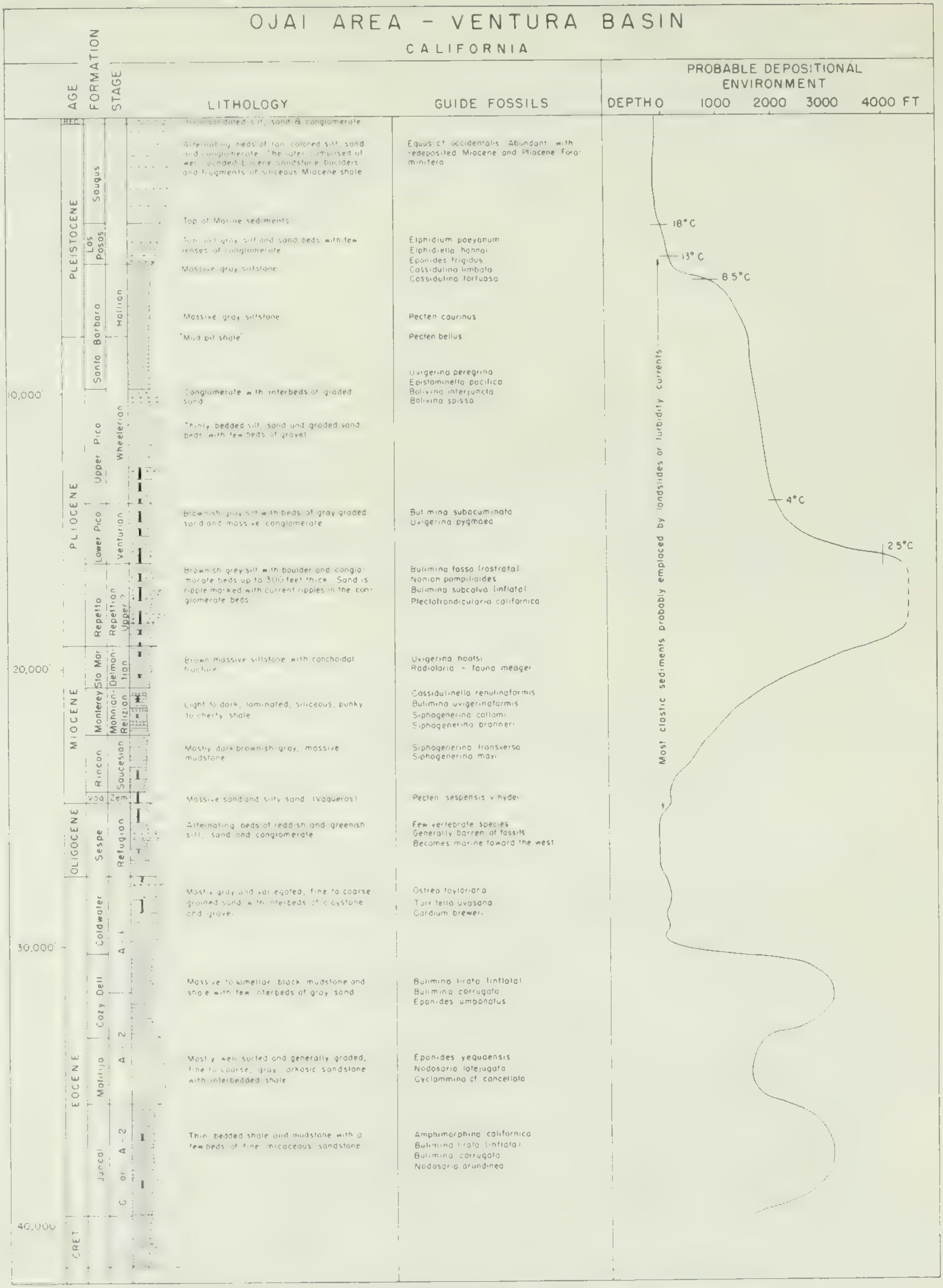

FIGURE 7. Composite section and foraminiferal guide fossils, Ojai area—Ventura basin.

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6. CENOZOIC LAND LIFE OF SOUTHERN CALIFORNIA

By Donald E. Savage[*] and Theodore Downs,[†]
with illustrations by Owen J. Poe[‡]

Introduction. Today the streets and highways of southern California teem with Man and his automobile, and form a part of the swarming mechanical panorama that centers about Greater Los Angeles. This is a scene of impressive contrast compared to the quiet though active drama of prehistoric life that once existed in this same region. And the land life of the past was only a part of the prehistoric scene, as southern California is well known for its great thicknesses of rock strata packed with invertebrate remains and for its astonishing records of marine fish, birds, and mammals. We can present but a limited view of one segment of this fascinating story, the Cenozoic land life.

Our vistas of the life of ancient times direct us not only toward the mountain-encircled Los Angeles basin, but northward, past the Tehachapis and the Panamints; eastward, over the San Gabriels, San Bernardinos, and Santa Anas into the Mojave Desert and the Imperial Valley; southward, past Palomar Mountain and on toward Baja California. We look backward in time to the California veldts, abounding in mastodons, rhinos, and camels; backward to the California tropical savannas, replete with tree ferns and broad-leafed evergreens. This story of the Cenozoic history begins with the Paleocene, the earliest period of that era.

Earliest. Near Elsinore, in Riverside County, certain outcrops of rock have been mapped as "Martinez" formation. From these beds have been collected leaf impressions of plants that do not grow wild in California today: tree ferns, palms, large-leafed evergreens. The same type of vegetation now grows only far to the south in tropical savanna country. This is a characteristic early Cenozoic (Paleocene) flora, very similar to floras from Paleocene rocks in New Mexico and Colorado. If the temperature and moisture requirements of the fossil plants were anything at all like those of similar living plants—and paleontologists believe they were—then parts of the land area of southern California back in Paleocene time must have been tropical savanna, drenched by heavy rains that probably fell during the warm season of the year. The flora near Elsinore is the earliest record of Cenozoic land life now known from southern California.

On the flanks of the El Paso Mountains, in the northwest corner of the Mojave Desert in Kern County, lies the Goler formation. Fragments of turtle and crocodile have been found here, but the main record of land life consists of impressions of leaves that represent tree ferns, magnolia, sapotá and other broad-leafed evergreens of tropical to sub-tropical types. Paleobotanists date this flora tentatively as Paleocene to early Eocene. The Mojave countryside at that time must have resembled the Elsinore district of slightly earlier (?) days . . . uniquely different from the Mojave today, wasn't it?

Early. Just north of San Diego, fossil bones have been discovered in the uppermost Rose Canyon shale and in the overlying Poway conglomerate. The animals here have been called the *Poway fauna* and constitute, at present, the earliest record of land mammals in California. Strange forms are represented (see their technical names in the pictorial maps that follow): lemur-monkeys and monkey-like insectivores, several primitive rodents that are distantly related to squirrels and mountain "beavers," and a short-faced brontothere and his cousin *Amynodon* (a rhinoceros not closely related to living types). This fauna has been dated UINTAN (late Eocene). Leaf and seed eaters are abundant; some were ground-running forms, and others probably lived in trees. The larger animals were herbivorous and browsers. We conclude from the mammals that woodlands were prevalent, but admit willingly the possible existence of grassland meadows among these forests. Fossil plants would give us a better picture of the Uintan Poway countryside, but they are not yet known from the area.

Seven thousand feet or more of nonmarine sediments are exposed around Santa Susana, Fillmore, and Santa Paula in Ventura County. These beds, called the Sespe formation, contain assemblages of mammals ranging in age from UINTAN (late Eocene) to ARIKAREEAN (early Miocene) but have yielded no fossil plants. The oldest fauna, *Tapo Ranch*, is in the Simi Valley; it is Uintan in age but perhaps is slightly younger than the Poway fauna. Lemur-monkeys, *Tapocyon* and *Miacis* (primitive dog-like carnivores), opossums, multitudes of rodents, small deer-like animals, and early "tapirs" make up the bulk of this fauna.

Higher in the section, and in the same area, is found the *Pearson Ranch* fauna (the famous Cal Tech locality 150 in particular). A

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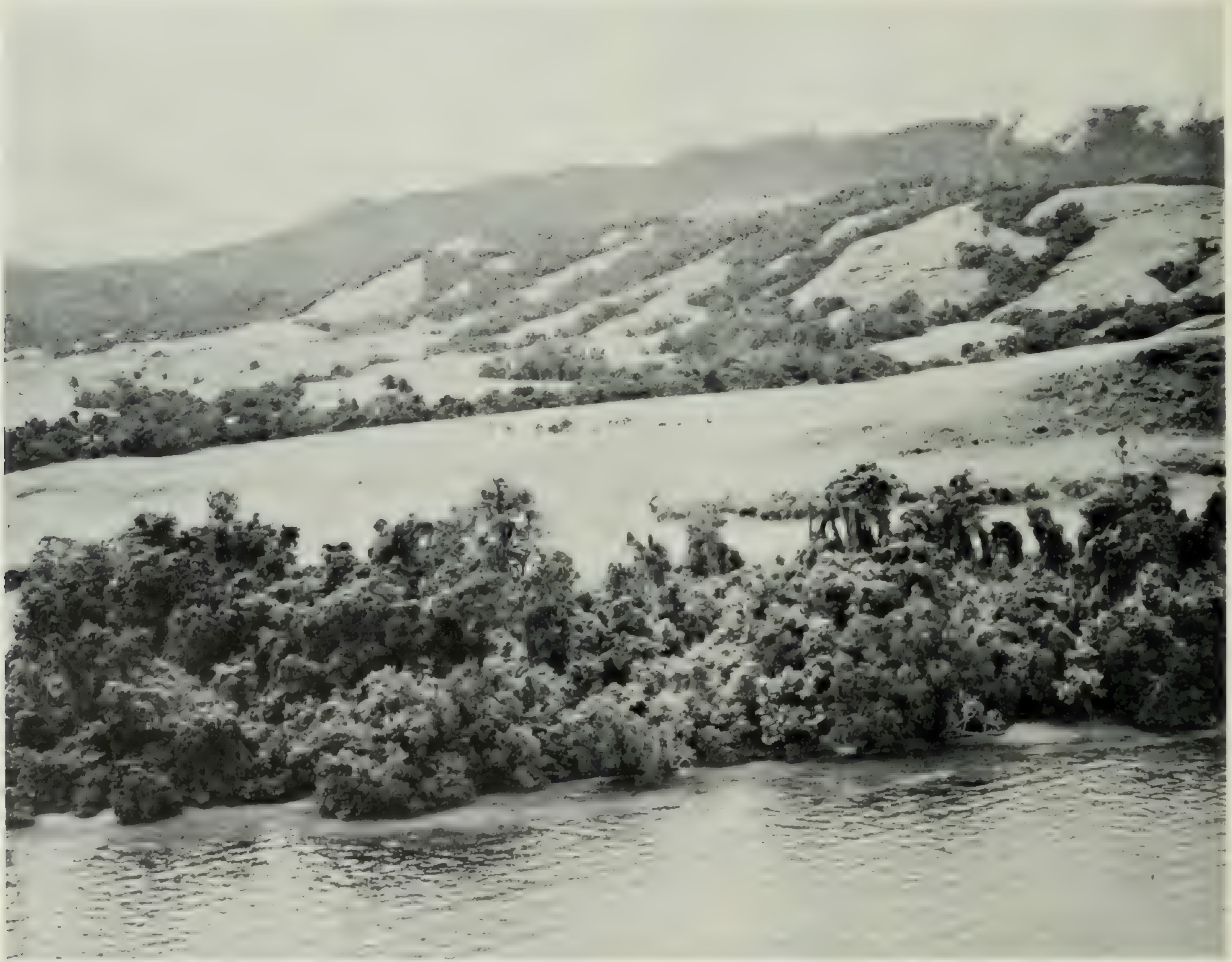

FIGURE 1. A neotropical savanna. The regions around Elsinore and Goler may have looked like this in Paleocene to early Eocene times.

large assemblage of early hyaena-like carnivores, lemur-monkeys, insectivores, rodents, brontotheres, rhinos, and *Simimeryx* ("deerlets") come from here and are dated DUCHESNIAN (latest Eocene). *Teleodus*, a brontothere like the one found in the Pearson Ranch fauna, was discovered in the *type* Sespe formation on Sespe Creek; hence we say that at least part of the type Sespe formation is probably Duchesnian in age. These late and latest Eocene occurrences abound in plant-eaters of the browsing type; therefore it may be concluded that the "Sespe" country had plenty of forests, perhaps best developed in well-watered stream valleys.

A group of mammals of CHADRONIAN age (early Oligocene) was collected from the Titus Canyon formation, in the Grapevine Mountains at the north end of Death Valley. Rodents, dogs, brontotheres, rhinos, *Mesohippus* (small browsing horses), tapirs, creodonts, camelids, and *Leptomeryx* ("deerlets") from this location all suggest a wooded and watered savanna country of those times that would be difficult to conceive from a look at the present-day terrain!

We have not been lucky enough to find mammals in California comparable to the remarkable ORELLAN (mid-Oligocene) faunas of the Great Plains region, and the mid-Eocene through early Miocene floral record in southern California has yet to be discovered.

Back in the Sespe formation again, at the *Kew quarry* in the Las Posas Hills and in part of the section at South Mountain, mammals have been found that appear to be WHITNEYAN (late Oligocene) in age . . . perhaps latest Whitneyan. The particular kinds of rabbits, squirrels, field mice, small and medium-sized dogs, sabre-toothed cats, small horses, rhinoceroses, *Hypertragulus* ("deerlets"), and oreodonts give this fauna a much more modern appearance than the Titus Canyon array. There is little evidence to indicate, however, that the habitat of the Kew quarry mammals was greatly different from that existing at Titus Canyon several million years previously.

Middle-Aged. Four to six hundred feet below the top of the Sespe formation at South Mountain have been found an oreodont, *?Mesoreodon hesperus* (Stock), and a gopher-like rodent. These have been tentatively dated ARIKAREEAN (early Miocene) on the basis of the better-known sequence of these groups in the Oligocene and Miocene rocks of the Great Plains region.

At Tecuya Creek in Kern County, just a short distance off U. S. Highway 99, are nonmarine red beds that underlie and grade into the famous Vaqueros marine sandstone. Bone hunters have found tree squirrel, a small running rhinoceros, "deerlets," *Daphoenus* (an early bear-dog), and a large oreodont in these Tecuya beds. The Tecuya fauna is dated the same as the uppermost South Mountain Sespe beds: ARIKAREEAN. In early Miocene time this locality apparently was a flood plain bordering the coast of a seaway. Again, if plants were known from here, they could supply a much better idea of the climate at that time.

Not far from Newhall and Saugus, in the eastern part of the Ventura basin in Los Angeles County, lies the Tick Canyon formation. The bones discovered in these deposits were tantalizingly few, but pocket mice, rabbits, *Parahippus* (a moderate-sized browsing-grazing horse), *Merychyus* (slender-limbed oreodonts), and camelids were there. One species of bird from the Tick Canyon formation in Vasquez Canyon is *Miohierax stocki* Howard, a hawk. This is the earliest well-preserved specimen of bird thus far known in the State, although an unidentifiable bird bone is known from the mid-Eocene of the Mt. Diablo district in northern California. These vertebrates are dated as late ARIKAREEAN (early Miocene) or early HEMINGFORDIAN (early mid-Miocene). The horse and the slender-limbed oreodont had teeth better adapted for grazing than their earlier relatives; this suggests that more grasslands existed, perhaps as broad divides between wooded streams.

Not far from Monolith in Kern County, high up in the mountains where the Tehachapis join the Kiavahs and the Sierras, lies the Phillips Ranch—Cache Peak district. Here the fossil mammalian faunas range in age from HEMINGFORDIAN (mid-Miocene) to BARSTOVIAN (late Miocene). Preliminary investigations by Dr. J. P. Buwalda have revealed very primitive forms of *Merychippus* (grazing-browsing horses), small and large camelids, chalicotheres (related to horses and rhinos but with claws on their toes), and small carnivores in the *Phillips Ranch* fauna (Hemingfordian). In the younger *Cache Peak* fauna (Barstovian) he found two types of *Merychippus*, *Hypohippus* (a horse not closely related to living forms), camels, oreodonts, paleomerycids ("deer"), prongbucks, and a cat.

A large collection of plants from the same section and from about the same stratigraphic level as the Phillips Ranch fauna, the *Tehachapi flora*, includes 69 trees and shrubs that have been dated as early middle Miocene. The assemblage most closely resembles the modern flora of northern Mexico, although some of the Tehachapi plants are now found only in southern California. It has been concluded that the Tehachapi flora lived on the inland slopes of a mountainous area in a rather dry, continental climate. Savanna-woodland, riparian (stream border), chaparral, and arid subtropical scrub associations were there. Living equivalents of the Tehachapi plants are found in regions of 15 to 20 inches rainfall and mild, generally frostless winters.

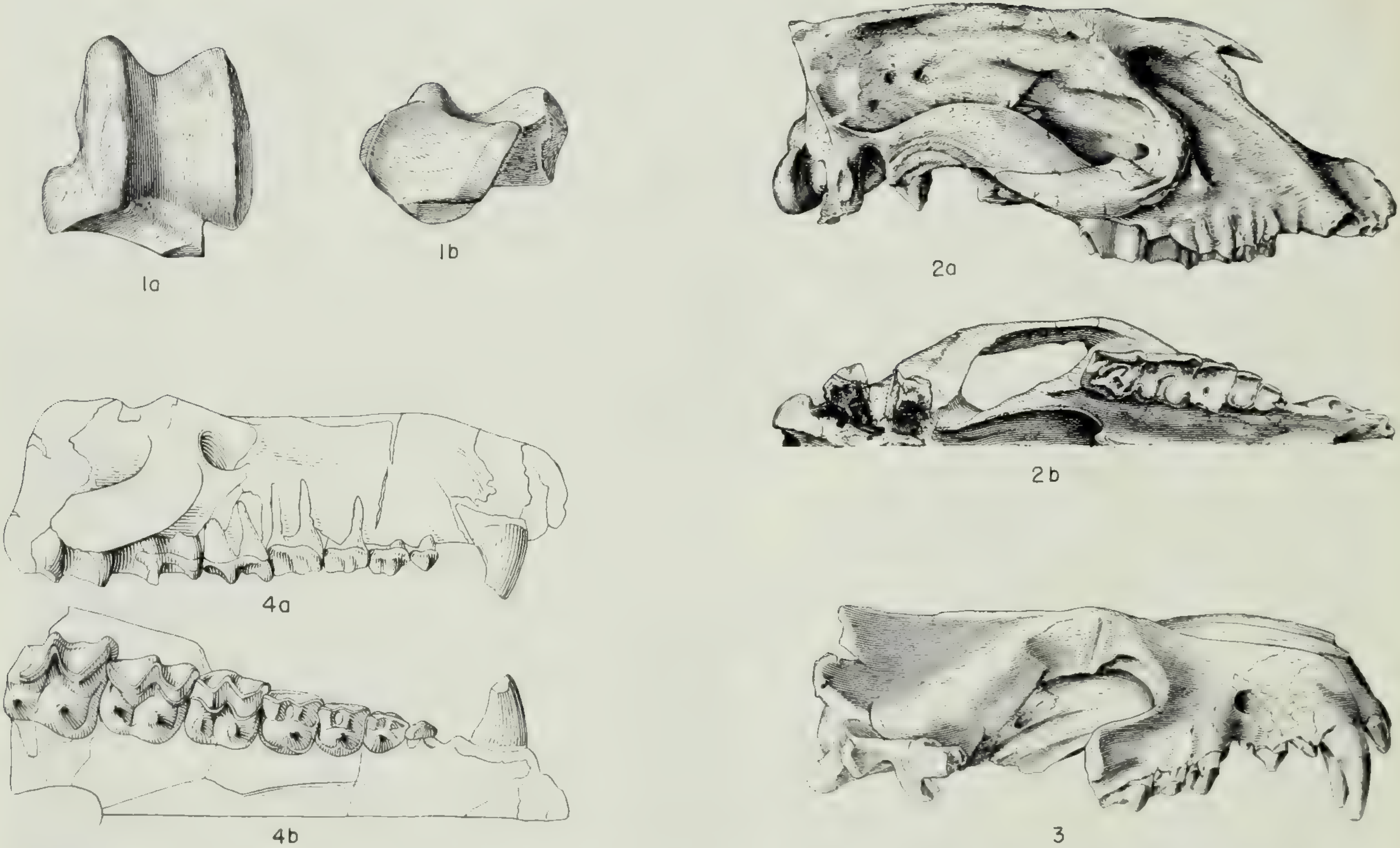

FIGURE 2. Early animals. 1. *Eotrigonias(?) mortivallis* Stock, astragalus (ankle bone) of a rhinoceros, x2/3, Titus Canyon fauna, Chadronian age (Stock, 1949, fig. 3). 2. *Amynodontopsis bodei* Stock, lateral and palatal views of an amynodont rhinoceros skull, x1/6, Pearson Ranch fauna, Duchesnian age (Stock, Nat. Acad. Sci. Proc., vol. 19, pp. 762-767, fig. 1, 1933). 3. *Hyaenodon vetus* Stock, lateral view of the skull of an early creodont carnivore, x1/3, Pearson Ranch fauna, Duchesnian age (Stock, Nat. Acad. Sci. Proc., vol. 19, pp. 434-440, fig. 1, 1933). 4. *Metarhinus(?) pater* Stock, lateral and palatal views of a brontothere upper cheek-tooth series, x1/3, Poway fauna, Uintan age (Stock, Nat. Acad. Sci. Proc., vol. 23, pp. 48-53, pl. 1, 1937).

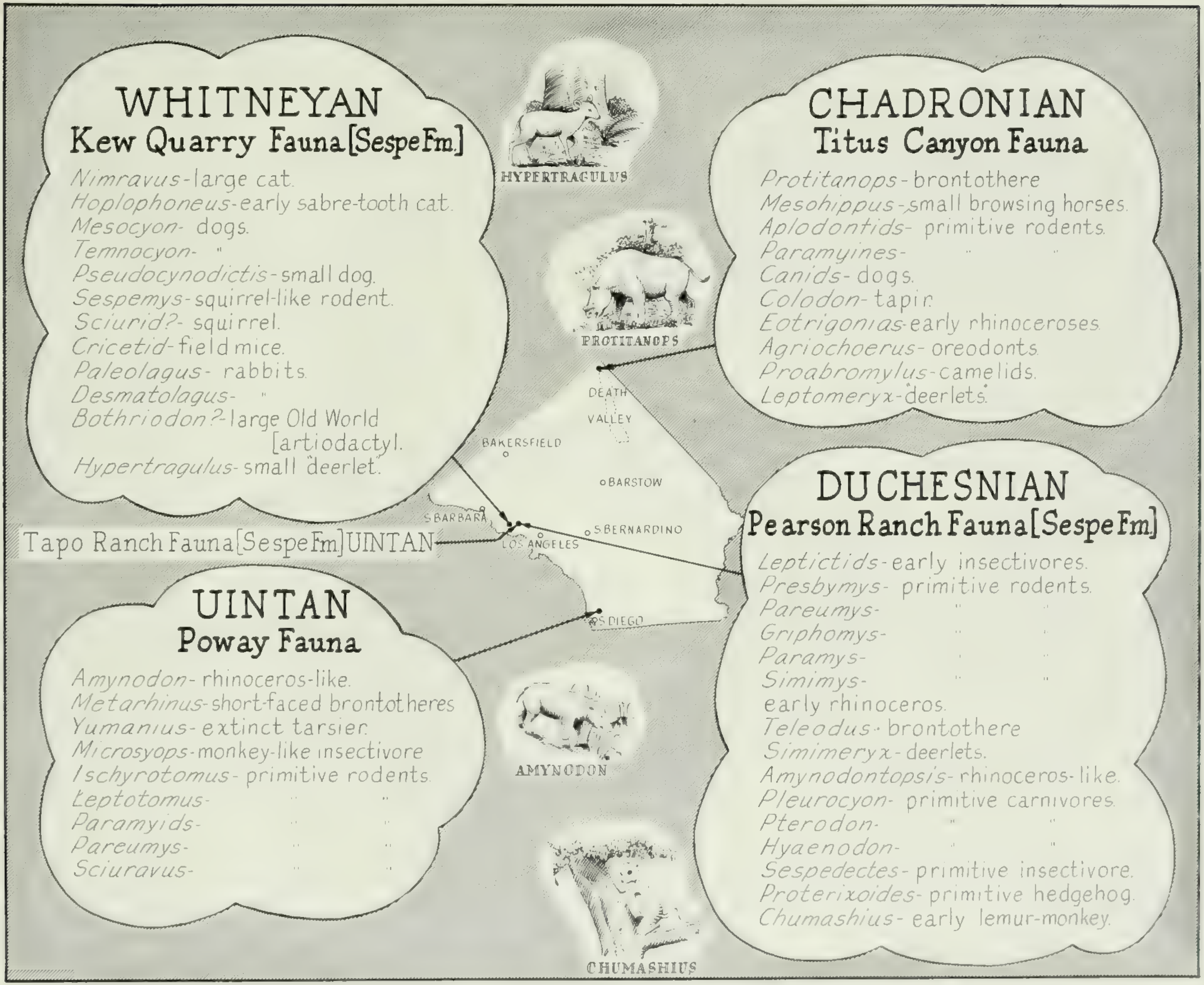
WHITNEYAN
Kew Quarry Fauna [Sespe Fm.]
Nimravus - large cat.
Hoplophoneus - early sabre-tooth cat.
Mesocyon - dogs.
Temnocyon - "
Pseudocynodictis - small dog.
Sespemys - squirrel-like rodent.
Sciurid? - squirrel.
Cricetid - field mice.
Paleolagus - rabbits.
Desmatolagus - "
Bothriodon? - large Old World [artiodactyl.
Hypertragulus - small "deerlet".
HYPERTRAGULUS
CHADRONIAN
Titus Canyon Fauna
Protitanops - brontothere
Mesohippus - small browsing horses.
Aplodontids - primitive rodents.
Paramyines - " "
Canids - dogs.
Colodon - tapir.
Eotrigonias - early rhinoceroses.
Agriochoerus - oreodonts.
Proabromylus - camelids.
Leptomeryx - "deerlets".
PROTITANOPS
DEATH VALLEY
BAKERSFIELD
BARSTOW
S. BARBARA
LOS ANGELES
S. BERNARDINO
S. DIEGO
Tapo Ranch Fauna [Sespe Fm.] UINTAN
DUCHESNIAN
Pearson Ranch Fauna [Sespe Fm.]
Leptictids - early insectivores.
Presbymys - primitive rodents.
Pareumys - " "
Griphomys - " "
Paramys - " "
Simimys - " "
early rhinoceros.
Teleodus - brontothere
Simimeryx - deerlets.
Amynodontopsis - rhinoceros-like.
Pleurocyon - primitive carnivores.
Pterodon - " "
Hyaenodon - " "
Sespedectes - primitive insectivore.
Proterixoides - primitive hedgehog.
Chumashius - early lemur-monkey.
UINTAN
Poway Fauna
Amynodon - rhinoceros-like.
Metarhinus - short-faced brontotheres
Yumanius - extinct tarsier.
Microsyops - monkey-like insectivore
Ischyrotomus - primitive rodents.
Leptotomus - " "
Paramyids - " "
Pareumys - " "
Sciuravus - " "
AMYNODON
CHUMASHIUS

FIGURE 3. Early and earliest faunas.

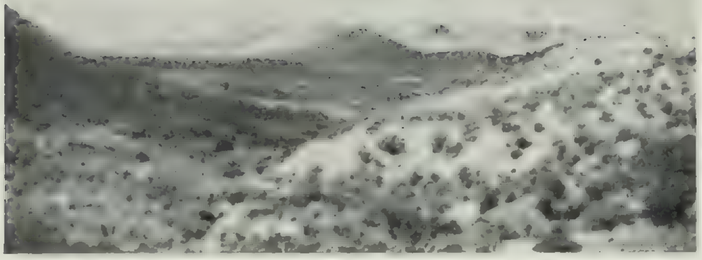

FIGURE 4. A region of savanna-woodland, scrub, and grassland. The mid-Miocene Tehachapi district had this appearance.

Near Barstow, in San Bernardino County, there occurs a fossil mammal fauna that is especially important to the people who study geologic dating problems in the nonmarine Cenozoic of North America. This is the *Barstow fauna* from the Barstow formation, type fauna of the BARSTOVIAN provincial age (late Miocene). Fresh-water shells are abundant locally and are being studied; but as for plants, only sabal palm is known. A great number of fossil bones have been collected here by different institutions in the United States. *Merychippus* (grazing-browsing horses) and camelids seem to have been most abundant; but *Hypohippus* (browsing horses), *Hemicyon* (dog-bears), pronghorns, peccaries, chipmunks, field mice, rabbits, dogs, sabre cats, true cats, mastodons, *Brachycrus* (large oreodonts), and even shrews have been described. Birds have been found here also; two hawks, several ducks, a gull, *Megapaloelodus* (a flamingo-like bird), and *Cyrtonyx* (a quail-like bird). The sediments were deposited in streams and lakes in a basin subjected to periodic falls of volcanic ash and dust; nevertheless, the mammals suggest that grassland was available. The palm indicates a type of vegetation similar to that living in warmer parts of northern Mexico today.

Extensive work by personnel of the United States Geological Survey, under the general supervision of Dr. D. F. Hewett, promises to increase our knowledge concerning many previously unknown or poorly known Miocene and Pliocene vertebrate faunas of the Mojave Desert.

Later. In the CLARENDONIAN age (early Pliocene), stream and lake deposits were being formed at many different places in southern California. Some communities were close to seaways, and the fossil plants in them thrived under the moderating influence of coastal weather; other communities were far inland, and their floras are continental in character. In southeastern Los Angeles County, a fossil flora has been collected from beds closely associated with Foraminifera- and mollusk-bearing deposits. This *Puente flora* apparently occupied the outermost coastal region and extended as far northward as Carmel (Monterey County), where the same plants occur in beds of the same age. Some of this flora—including lancewood, avocado, fig, palm, *Nectandra*, *Anona*, and *Coccoloba*—represents a relict subtropical forest that lived in sheltered coastward-facing valleys next to the sea. On adjacent exposed slopes was a woodland of evergreen oaks, Catalina ironwood, sycamore, and pine. There also is evidence of chaparral (scrub oak and mountain mahogany) on drier sites.

At Ricardo, in Kern County, beautifully colored nonmarine deposits contain both petrified wood and mammal bones. The *Ricardo* flora is found in beds lower than most of those containing the *Ricardo* fauna, but both are believed to be CLARENDONIAN in age. The flora is known mostly from studies of the fossil wood, although a few leaves are present. Live oak, pinyon pine, locust, cypress, buckbrush, acacia, desert thorn, and palm have been found. They suggest a woodland-savanna association, with chaparral and some arid subtropical scrub nearby. Precipitation was about 15 inches yearly as summer showers and winter rain. Summers were hot, but winters were mild and probably frostless.

The large Ricardo fauna, with *Pliohippus* and *Hipparion* (early grazing horses), dogs, hyaenoid dogs, bear-dogs, cats, rabbits, long-jawed mastodons, rhinoceroses, camels, pronghorns, weasels, oreodonts, Palaeomerycidae ("deer"), and *Branta howardae* Miller (a goose), must have thrived in a grassland-woodland community.

The Avawatz fauna, from near the south end of Death Valley, has mammals that are the same or very similar to the Ricardo types, and it is believed to be about the same age as the Ricardo.

Clarendonian vertebrate faunas of two different subages are found in the Tejon Hills, southeast of Bakersfield in Kern County. One is slightly older than the Ricardo; the other is about the same age.

A large flora and a few mammal specimens have been obtained from the Mint Canyon beds in the eastern Ventura basin (the same general area as the Tick Canyon formation). The beds are of Clarendonian age, as indicated by *Pliohippus*, *Hipparion*, and *Nannippus* (early grazing horses). Mastodons, dogs, rhinos, peccaries, rabbits, camels, and pronghorns were there, too. The flora, together with the mammals, indicates a characteristic live-oak woodland, chaparral, and arid subtropical scrub with grassland interspersed. This is an

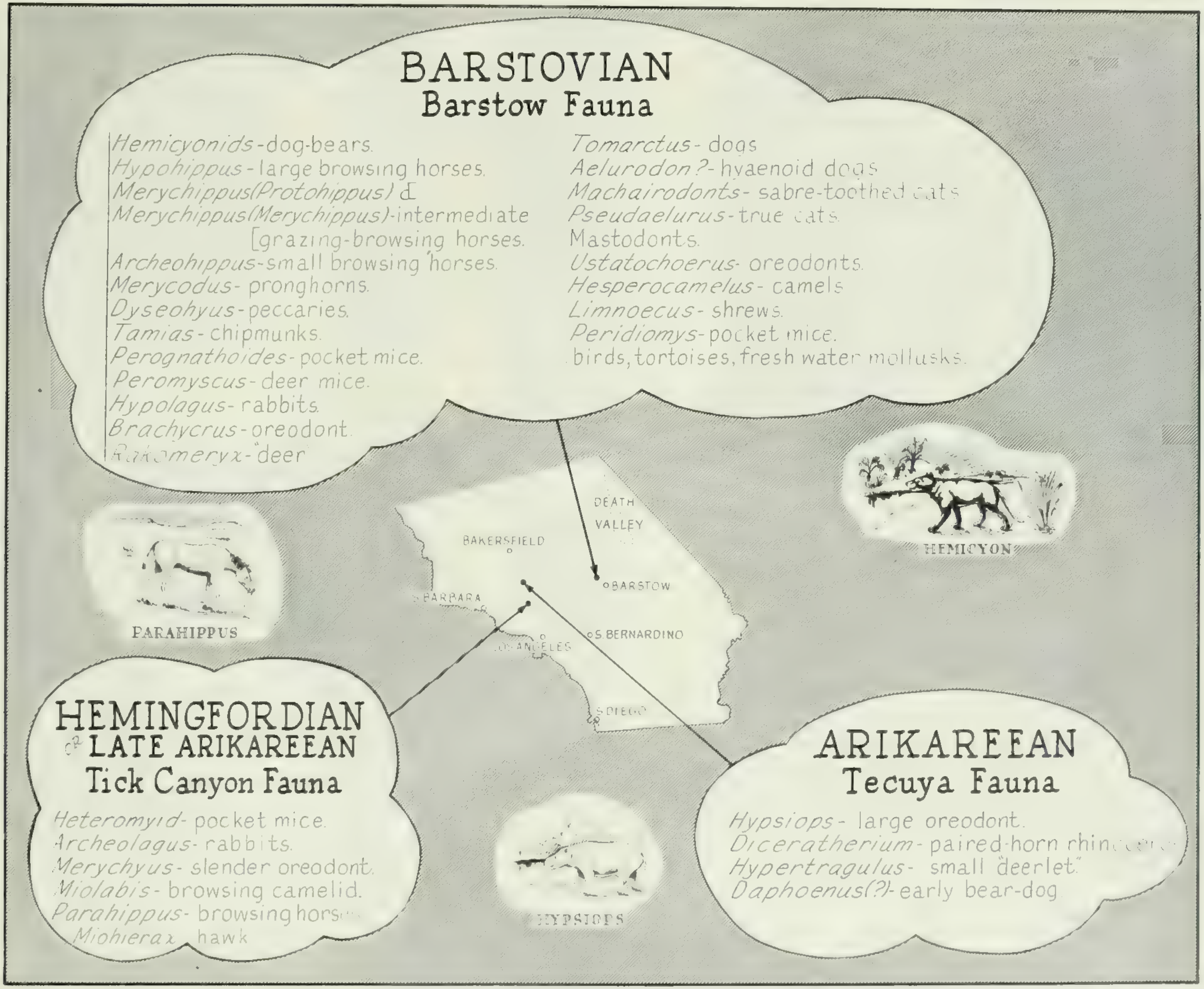

FIGURE 5. Middle-aged faunas.

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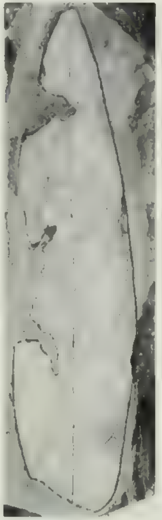
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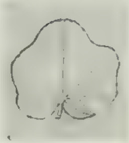
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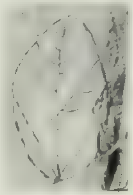
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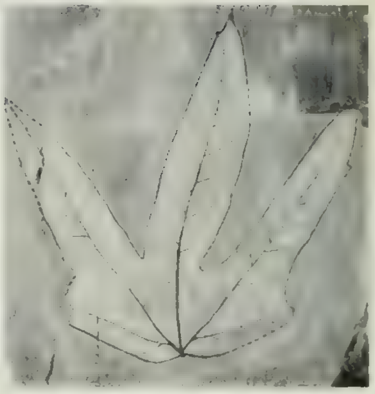
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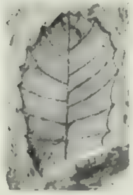
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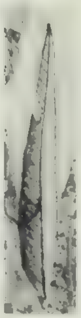
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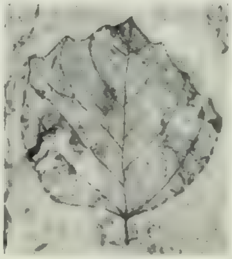
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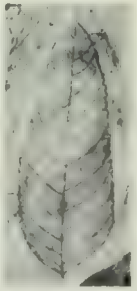
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FIGURE 6. Later plants. 1. A midsummer day at Ricardo in Clarendonian time (*photo by H. S. Gentry*). 2. *Persea coalingensis* (Dorf), avocado, x2/3, Piru Gorge flora, Hemphillian age (Axelrod, 1950, pt. 5, pl. 5, fig. 9). 3. *Fremontia coriacea* Axelrod, fremontia, x2/3, Piru Gorge flora, Hemphillian age (Axelrod, 1950, pt. 5, pl. 6, fig. 5). 4. *Ceanothus prespinosus* Axelrod, buckthorn, x2/3, Piru Gorge flora, Hemphillian age (Axelrod, 1950, pt. 5, pl. 6, fig. 3). 5. *Platanus paucidentata* Dorf, sycamore, x2/3, Piru Gorge flora, Hemphillian age (Axelrod, 1950, pt. 5, pl. 6, fig. 1). 6. *Quercus wislizenoides* Axelrod, live oak, x2/3, *Anaverde flora*, Hemphillian age (Axelrod, 1950, pt. 4, pl. 3, fig. 2). 7. *Sapindus oklahomensis* Berry, soapberry, x2/3, Mt. Eden flora, Hemphillian age (Axelrod, 1950, pt. 3, pl. 3, fig. 4). 8. *Populus sonorensis* Axelrod, cottonwood, x2/3, Mt. Eden flora, Hemphillian age (Axelrod, 1950, pt. 3, pl. 2, fig. 3). 9. *Arbutus prexalapensis* Axelrod, madrone, x2/3, Mt. Eden flora, Hemphillian age (Axelrod, 1950, pt. 3, pl. 3, fig. 11).

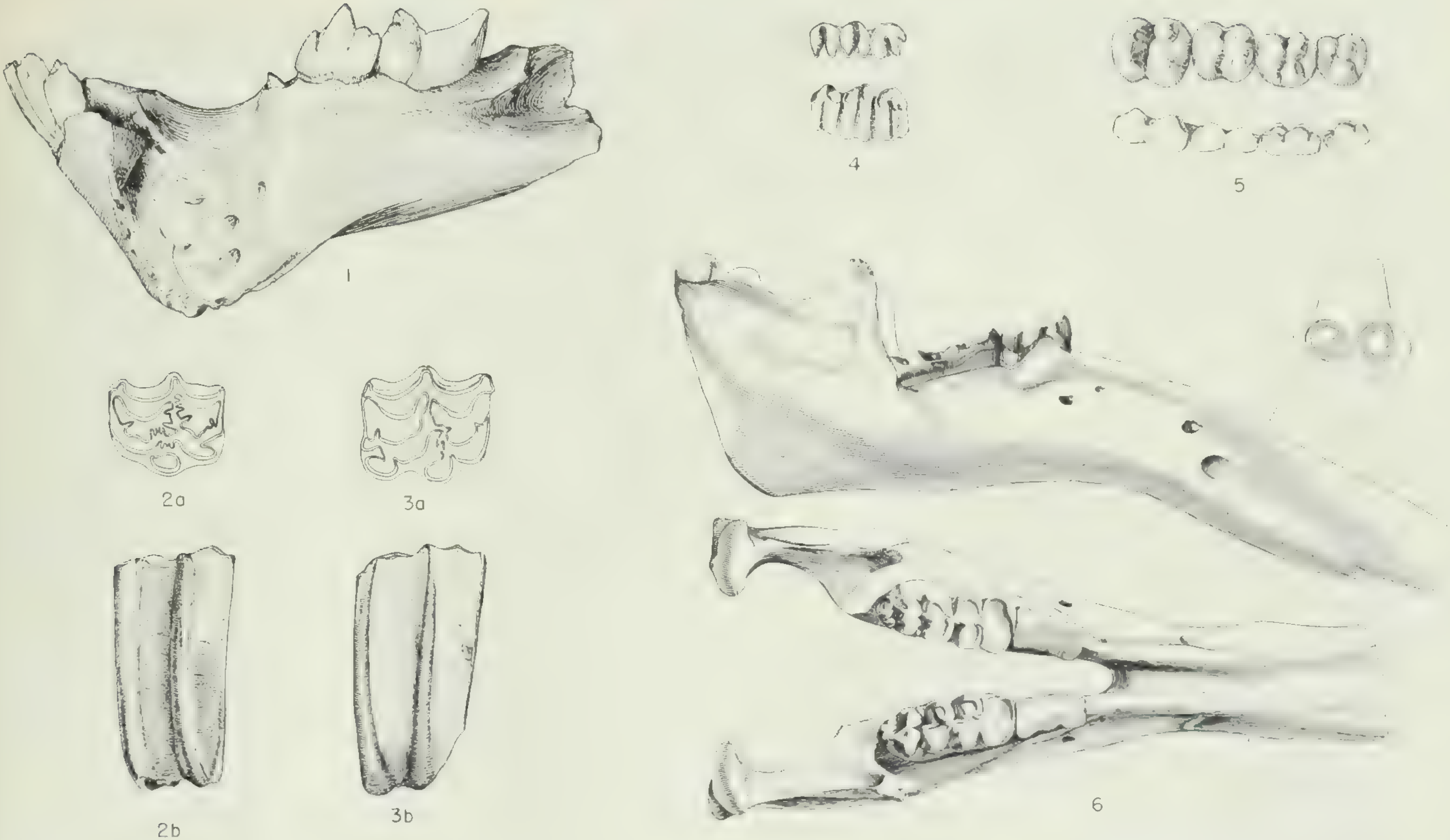


FIGURE 7. Later animals. 1. *Ischyrosmilus osborni* Merriam, left lower jaw of sabre-tooth cat, x2/3, Ricardo fauna, Clarendonian age (Merriam, 1919, fig. 155). 2. *Hipparion mohavense* Merriam, upper premolar of early three-toed grazing horse, x2/3, Ricardo fauna, Clarendonian age (Merriam, 1919, figs. 163, in part, and 164); a, view of grinding surface; b, view of outside of tooth. 3. *Pliohippus tantalus* Merriam, upper premolar of early single-toed grazing horse, x2/3, Ricardo fauna (Merriam, 1919, fig. 184, *P. "fairbanksi"* Merriam). 4. *Hypolagus edensis* Frick, lateral and grinding surface views of some upper cheek teeth of a rabbit, x4/3, Mt. Eden fauna, Hemphillian age (Frick, 1921, fig. 52). 5. *Prosthennops edensis* Frick, lateral and grinding surface views of upper cheek teeth of a peccary, x2/3, Mt. Eden fauna (Frick, 1921, fig. 58). 6. *Gomphotherium*, views of lower jaw and cross section of lower tusks of a long-jawed mastodon from late Clarendonian beds in northern California; this type is also found in the Ricardo fauna; x1/9 (Stirton, 1939, Univ. California Dept. Geol. Sci. Bull., vol. 24, no. 13, fig. 27).

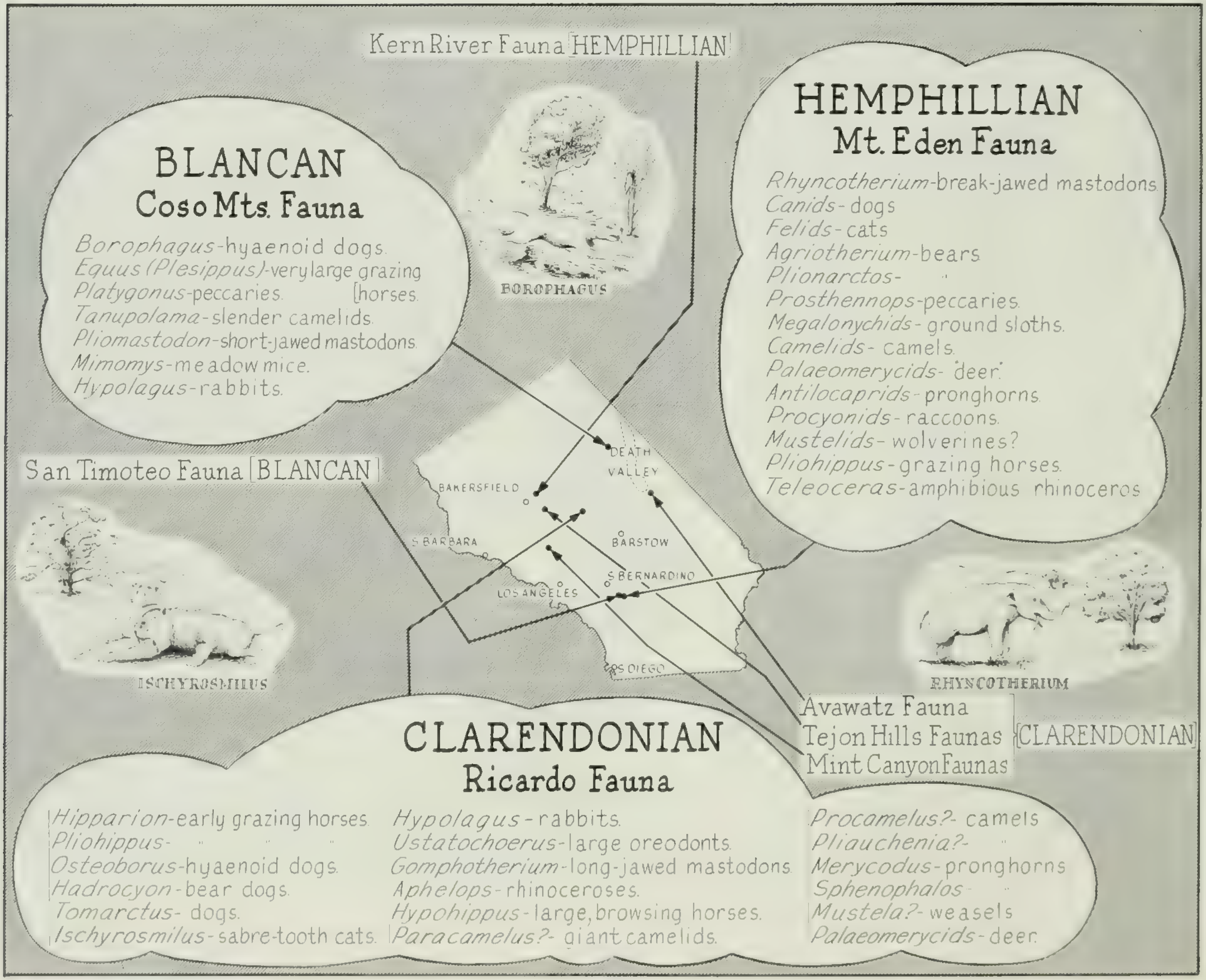


FIGURE 8. Later faunas.

interior flora, and Axelrod believes that hills lay between the Mint Canyon basin and the sea at the time these plants lived. Rainfall occurred throughout the year and totaled 15 to 20 inches; frosts were rare or absent.

Live-oak woodland, walnut woodland, digger-pine woodland, big-cone forest, chaparral, coastal sage, grassland, desert-border and arid subtropical scrub vegetation are all represented in rocks of HEMPHILLIAN age (mid-Pliocene) in southern California. Near Palmdale in Los Angeles County (*Anaverde* flora), at Piru Gorge in Los Angeles County (*Piru Gorge* flora), and near Beaumont in Riverside County (*Mt. Eden* flora) many fossil plants show the existence of these communities. In general the Hemphillian lowlands of southern California were somewhat as at present in terms of vegetation and climate. They were semiarid (12 to 20 inches of rainfall), but in those days there were regular summer showers and mild winters. According to Axelrod, who has described all these floras, the mid-Pliocene was the driest stage of the Tertiary in the Far West.

The *Kern River* fauna, from beds of the same name, comes from points northeast of Bakersfield where the Great Valley begins to grade eastward into the foothills of the mighty Sierra Nevada. Only a few of the specimens that were collected by parties from the California Institute of Technology have been described; they include *Eomellivora* (an extinct honey badger very similar to a species in the Pliocene of China), *Bassariscus* (a cacomistle or "ring-tailed cat"), *Brachypsalis* (an extinct carnivore in the weasel family), *Sarcoramphus* (a vulture), and *Parabuteo* (a hawk). *Pliohippus* (this particular species is an early single-toed grazing horse), rhinos, ground squirrels, field mice, rabbits, pronghorns, peccaries, and camels have been found there, also. We believe that the Kern River fauna represents the earlier part of the HEMPHILLIAN age (mid-Pliocene).

Fossil mammals are known from the Mt. Eden beds. The fauna, dated as later Hemphillian, includes *Rhynchotherium* (a strange mastodon with downturned tusks and lower jaw), dogs, cats, *Astrohippus* (a group of advanced grazing horses), dog-bears, peccaries, rhinos, ground sloths (new arrivals from South America, their earlier homeland), camels, pronghorns, and other forms.

Overlying the Mt. Eden beds are other mammal-bearing deposits, the beds of the San Timoteo formation. The few bones that have been found here show that giant land tortoises, camels, ground sloths, and true deer dwelt in the area. A large *Equus*, sometimes called *Plesippus*, probably is the most important animal in the San Timoteo fauna. This horse, quite similar to the modern horse, is a good guide fossil, telling us that the beds are BLANCAN (late Pliocene) in age.

Between Death Valley and the Sierra Nevada in Inyo County are the Coso Mountains. The Coso Mountains formation bears the finest Blancan mammal fauna in southern California. *Borophagus* (largest and last of the hyaenoid dogs), *Equus* (*Plesippus*), short-jawed mastodons, *Mimomys* (meadow mice), *Tanupolama* (slender-limbed camelid), and *Platygonus* (large peccary) make this fauna easily distinguishable from preceding ones. These animals must have lived in a region of abundant grassland, for the animals with high-crowned, grazing-type teeth are abundant.

Latest. Pleistocene time is not easy to subdivide on the basis of change and evolution of faunas or floras. It was too short. In California we are able to recognize only a twofold division: IRVINGTONIAN (earlier Pleistocene), named after the Irvington fauna in beds at the south end of San Francisco Bay, and RANCHOLABREAN (later Pleistocene), named after the fauna of Rancho La Brea.

In the Bautista beds of Riverside County we find *Equus* (a large true horse), *Odocoileus* (true deer), jack rabbits, ground sloths, camels, tapirs, and pronghorns that may be the same as a strange four-horned species at Irvington.

The Manix beds, near Barstow in San Bernardino County, have yielded an unusual assortment of fossil mammal specimens; practically all are fragments of limb bones. These beds may be BLANCAN to RANCHOLABREAN in age, but the evidence for exact dating is poor at present.

One of the most interesting records of past land life in southern California is the occurrence of mammoths on Santa Rosa, San Miguel, Santa Cruz, and San Nicolas Islands. Mammoths migrated into North America from Eurasia during Pleistocene time (post-Blancan). All known species on the mainland were the size of circus elephants, or larger . . . 10 to 14 feet in shoulder height. The island forms differ considerably from place to place, but most had a height of only 6 to 9 feet, particularly on Santa Rosa Island. Dr. Chester Stock believed that these island forms represent a population that got there sometime during the Pleistocene when the Santa Monica mountain area extended much farther out to sea than at present, and was a continuous land projection. Later, as this peninsula was cut up into islands, the mammoth population evolved into dwarfed forms. Dwarfed races of mammals are well known on islands; apparently this phenomenon results from inbreeding and an acceleration of evolution, which favors the survival of smaller and smaller individuals. Factors such as reduced area of range and reduced food

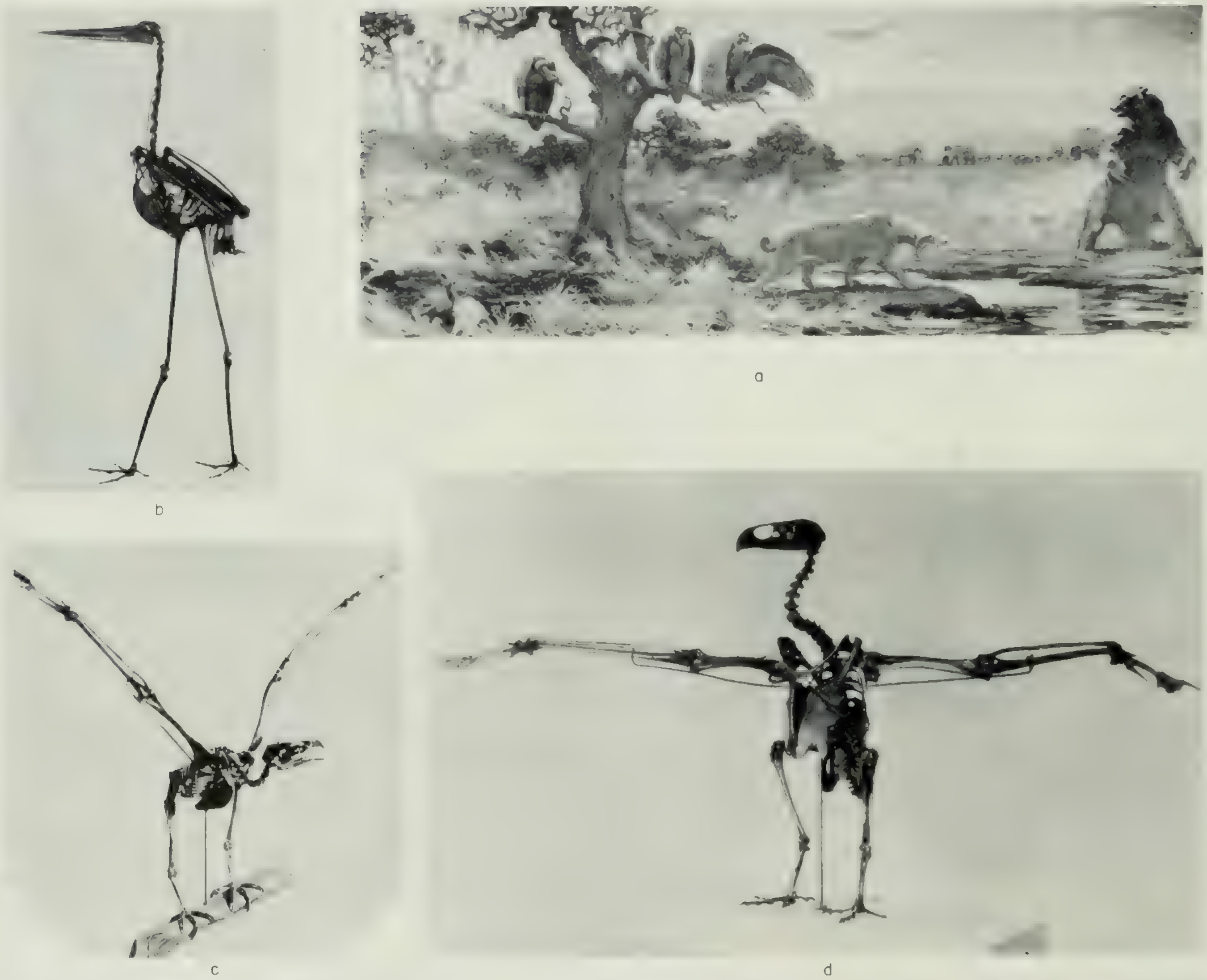


FIGURE 9. The Rancho La Brea scene. a, Mural in Los Angeles Museum depicting life at the site of the tar pits (*Charles R. Knight, artist*). b, ***Ciconia maltha*** Miller, an extinct stork about 5 feet tall. c, *Neogyps errans* Miller, an extinct eagle related to old world vultures. d, *Teratornis merriami* Miller, the great extinct condor-like vulture with wingspread of at least 12 feet. *All photos courtesy of Los Angeles County Museum.*

supply may be important in the development of such pygmies from normally huge beasts. Curiously enough, the only other fossil mammal known from the Channel Islands is a species of *Peromyscus* (deer mouse) from Santa Rosa. It was larger than its relatives in the area today.

The climate and topographic conditions of the Channel Islands are indicated by the *Willow Creek* fossil flora from Santa Cruz, and by the living flora of the island and adjacent mainland. All the species of plants in the fossil assemblage now live in coastal California: Douglas fir, closed-cone pine, Gowen cypress, pine mistletoe, wax myrtle, blue blossom, silk tassel bush, manzanita, and creek dogwood. A modern forest of this type is seen at Fort Bragg, 440 miles northward. The rainfall may have been about 35 inches over an 8-month period, with the mean temperature about 52°; fogs probably occurred almost daily through the rainless months. This seems to have been a southward extension of a northern flora, maybe at the time of maximum glacial development on the inland mountains and on the northern interior of the continent. Certain types of living plants are found only on these Channel Islands and on the adjacent mainland, a fact that also suggests a former land connection to the islands.

Animal and plant remains have been quarried from asphaltic deposits at Carpinteria, Santa Barbara County. This locality is unrivaled from the standpoint of showing a balanced sample of mammals, birds, marine mollusks, and land plants of the same geologic age . . . all are well represented. The *Carpinteria* flora is somewhat like the Willow Creek flora in that it is vegetation of a type now found on coastal California. Most of the Carpinteria plants are now living in the Monterey pine forest, 200 miles northward; thus the Carpinteria area evidently was cooler and more humid at the time of the plant accumulations. Conifers and manzanita are the plants most abundantly represented in the flora, which also includes Bishop, Monterey, and digger pines, Gowen cypress, California juniper, coast redwood, wax myrtle, coast live oak, California bay laurel, great-berried manzanita, and blue elderberry.

Among the Carpinteria mammals, the dire wolf, giant cat, camel, horse, and bison are extinct, and the deer mice, kangaroo rats, gophers, and meadow mice are most common. In contrast to the climatic conditions mentioned above, R. W. Wilson noted that some of the mammals must have lived in semiarid, open terrain and grassland.

All told, more than 60 species of birds have been found in the Carpinteria asphalt, and 36 percent of these are extinct. Strangely, few shore or wading birds were found. Most of the species indicate principally a woodland area in the region.

Quantities of fossil remains are known from another late Pleistocene asphalt deposit at McKittrick, in Kern County. Of the 43 species of mammals found there, 20 are extinct; and of 88 species of birds, 9 are no longer living. The regional environment was much the same as it is there today.

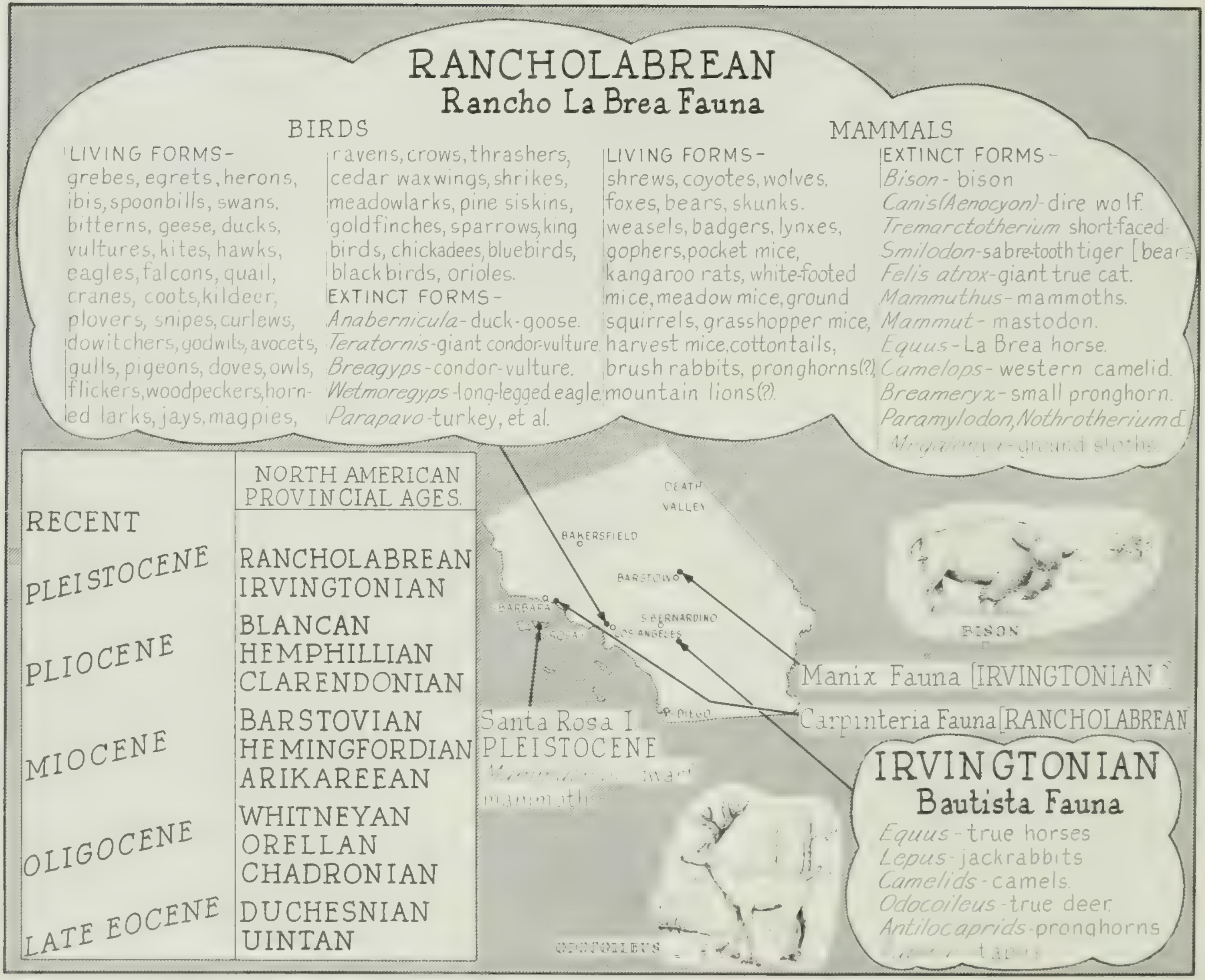
In what is now Hancock Park, along Wilshire Boulevard in Los Angeles, lie 23 acres of ground that have yielded one of the most famous concentrations of past bird and mammal life in the world. This is *Rancho La Brea*, asphalt death trap for thousands of early native Californians. The fauna from these tar springs is more than worthy of being the type for the later Pleistocene provincial age in North America: RANCHOLABREAN.

The story of Rancho La Brea is so well portrayed by the exhibits at Hancock Park and at the Los Angeles County Museum, and it has been so thoroughly documented by research workers from the Los Angeles Museum, the California Institute of Technology, and the University of California, that a brief resume does no justice to the fascinating and absorbing story. In Stock's own words (1929, p. 289):

"The scene at Rancho La Brea, as visualized from a study of the Pleistocene mammalian life of this time and place, possessed on occasion apparently a sombreness deepened by dramatic significance. These tar traps during their active periods appear verily to have been ulcerous spots on the face of Nature, where death mocked the comparative serenity of life in the open.

"Within the borders of the pools where the petroliferous ooze exerted a peculiarly tenacious grip on the victims, there doubtless could be seen at times a curious array of mired hosts pitted against a common adversity. Immediately without the confines of the trap the unwelcome flesh-eater lent his presence as a dominant participant in the drama, truculently watchful of the prey so near at hand, yet wholly unmindful of the end destined to overtake both fellow and foe alike. The cries and struggles of the wounded, the not infrequent stench of offal, and the fierce combats of those not yet mired may well have made of the individual trap a quagmire whose horrors and iniquities are now veiled with the inevitable passing of geologic time."

To appreciate fully the magnitude of this amazing assemblage of animals, one should read the papers of J. C. Merriam, Chester Stock, Loye Miller, Alden Miller, Hildegarde Howard, and others. The Los Angeles County Museum's handbook, "Rancho La Brea," presents a summary treatment by Stock, and contains a bibliography. Almost 50 species of mammals; more than 110 species of birds; a few snakes, turtles, and toads; and a score or more of mollusks, millipeds, beetles, and bugs are presently recognized. The plant record is relatively


RANCHOLABREAN
Rancho La Brea Fauna
BIRDS
LIVING FORMS - grebes, egrets, herons, ibis, spoonbills, swans, bitterns, geese, ducks, vultures, kites, hawks, eagles, falcons, quail, cranes, coots, kildeer, plovers, snipes, curlews, dowitchers, godwits, avocets, gulls, pigeons, doves, owls, flickers, woodpeckers, horned larks, jays, magpies, ravens, crows, thrashers, cedar waxwings, shrikes, meadowlarks, pine siskins, goldfinches, sparrows, king birds, chickadees, bluebirds, black birds, orioles.
EXTINCT FORMS -
Anabernicula - duck-goose.
Teratornis - giant condor-vulture.
Breagyps - condor-vulture.
Wetmoregyps - long-legged eagle.
Parapavo - turkey, et al.
MAMMALS
LIVING FORMS - shrews, coyotes, wolves, foxes, bears, skunks, weasels, badgers, lynxes, gophers, pocket mice, kangaroo rats, white-footed mice, meadow mice, ground squirrels, grasshopper mice, harvest mice, cottontails, brush rabbits, pronghorns(?), mountain lions(?).
EXTINCT FORMS -
Bison - bison
Canis(Aenocyon) - dire wolf.
Tremarctotherium short-faced [bears
Smilodon - sabre-tooth tiger
Felis atrox - giant true cat.
Mammuthus - mammoths.
Mammut - mastodon.
Equus - La Brea horse.
Camelops - western camelid.
Breameryx - small pronghorn.
Paramylodon, Nothrotherium &
Megalonyx - ground sloths.
DEATH VALLEY
BAKERSFIELD
BARSTOW
S. BARBARA
S. BERNARDINO
LOS ANGELES
S. ROSA
S. DIEGO
BISON
Manix Fauna [IRVINGTONIAN]
Carpinteria Fauna [RANCHOLABREAN]
Santa Rosa I.
PLEISTOCENE
Mammuthus - dwarf mammoth
IRVINGTONIAN
Bautista Fauna
Equus - true horses
Lepus - jackrabbits
Camelids - camels.
Odocoileus - true deer.
Antilocaprids - pronghorns
Tapirus - tapirs
ODOCOILEUS

	NORTH AMERICAN PROVINCIAL AGES.
RECENT	
PLEISTOCENE	RANCHOLABREAN IRVINGTONIAN
PLIOCENE	BLANCAN HEMPHILLIAN CLARENDONIAN
MIOCENE	BARSTOVIAN HEMINGFORDIAN ARIKAREEAN
OLIGOCENE	WHITNEYAN ORELLAN CHADRONIAN
LATE EOCENE	DUCHESNIAN UINTAN

FIGURE 10. Latest faunas.

poor, with only pine, cypress, juniper, live oak, manzanita, cocklebur, blue elderberry, and hackberry thus far recorded, but it indicates more interior and arid conditions than those at Carpinteria. There also is evidence in these deposits for the transition of life from late Pleistocene to Recent, and human remains were found in one pit.

RANCHOLABREAN-age faunas can be identified by predominance of living species of small mammals and birds, coupled with a few extinct (usually large) forms. We believe that *Bison* is a good guide fossil for the age.

Pleistocene marine or near-shore deposits at Newport Bay in Orange County, and at San Pedro, Santa Monica, and Playa del Rey in Los Angeles County, have yielded land mammals (ground sloth, horse, tapir, small and large camel, bison, mammoth, and sabretooth cat) and birds (eagle, vulture, quail, and meadow lark), along with forms that frequent the sea. In all marine deposits of this type from which birds have been recovered, the extinct diving goose, *Chendytes*, is the dominant form. This bird apparently was flightless.

Conclusion. And so we terminate our discussion—a faint glimpse into the fantastic labyrinth that is the complete record of changing life communities, climates, and topographies of southern California in past days.

No summary statement on this subject can fail to pay homage to the pioneer work of Dr. John C. Merriam of the University of California. Research writings and guiding activities of the late Dr. Chester Stock, Chairman of the Division of Geological Sciences at the California Institute of Technology, together with the studies he inspired his students and colleagues to accomplish, were responsible for most of the descriptions in these pages. Dr. Loye H. Miller, Professor Emeritus of Biology of the University of California and "Padre" to his many admirers, is no less inspirational to the succeeding generations. He is similarly responsible for the comprehensive treatment of the fossil birds of California, though this was but a small facet of his many productive interests.

Present workers who have added significantly to our knowledge of the history of land life in southern California include Dr. Robert W. Wilson of the Museum of Natural History at the University of Kansas; Dr. Hildegarde Howard, Chairman of the Division of Sciences, Los Angeles County Museum; and Dr. Daniel I. Axelrod, Professor of Geology in the University of California, Los Angeles. Axelrod has published the greatest amount of pertinent information about the floras and land paleoecology of this area, and has graciously allowed the writers to paraphrase his published statements and to cite information from his unpublished manuscripts. To him we are especially grateful.

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7. MARINE-NONMARINE RELATIONSHIPS IN THE CENOZOIC SECTION OF CALIFORNIA*

BY J. WYATT DURHAM,† RICHARD H. JAHNS,‡
AND DONALD E. SAVAGE §

INTRODUCTION

Highly fossiliferous marine sediments of Cenozoic age are widely distributed in the coastal parts of central and southern California, as well as in the Sacramento-San Joaquin Valley region farther inland. Even more widespread are nonmarine, chiefly terrestrial, sequences of Cenozoic strata, many of which contain vertebrate faunas characterized by a dominance of mammalian forms. These strata are most abundant in the Mojave Desert region and in the interior parts of areas that lie nearer the coast.

Marine and nonmarine strata are in juxtaposition or interfinger with one another at many places, especially in the southern Coast Ranges and the San Joaquin basin to the east, in the Transverse Ranges and adjacent basins, and in several parts of the Peninsular Range region and the Coachella-Imperial Valley to the east. These occurrences of closely related marine and nonmarine deposits permit critical comparisons between the Pacific Coast mammalian (terrestrial) and invertebrate (marine) chronologies, and it is with these comparisons—examined in the light of known stratigraphic relations—that this paper is primarily concerned.

The writers have drawn freely upon the published record for geologic and paleontologic data. In addition, Durham has reviewed many of the invertebrate faunas and has checked the field relations of marine strata in parts of the Ventura and Soledad basins, the Tejon Hills, and the Cammatta Ranch; Jahns has studied new vertebrate material from the Soledad basin and has mapped this area and critical areas in the vicinity of San Diego, in the Ventura basin, and in the Caliente Range; and Savage has made a detailed appraisal of the vertebrate assemblages, and has mapped critical areas in the Tejon Hills. The areas and localities that have been most carefully scrutinized are shown in figure 1.

The manuscript was reviewed in detail by G. Edward Lewis of the U. S. Geological Survey, who made numerous comments and suggestions that resulted in considerable improvement. It should be noted that his views are not wholly compatible with some of those expressed in this paper, and that his critical appraisal thus was particularly helpful.

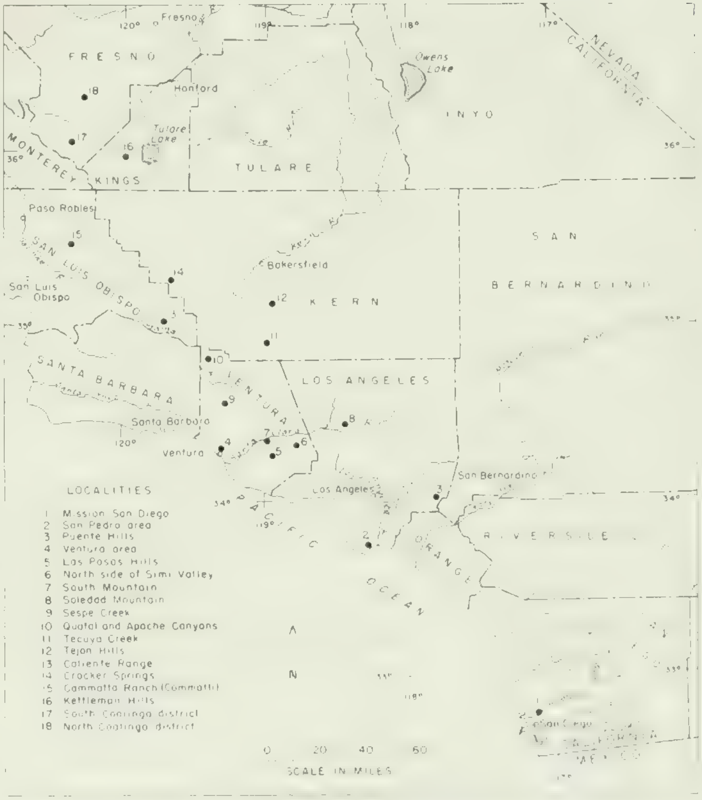

FIGURE 1. Index map of a part of southern California, showing locations of marine-nonmarine tie-ins discussed in the text.

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* A contribution from the Museum of Paleontology of the University of California, Berkeley; Contribution No. 664, Division of the Geological Sciences, California Institute of Technology.

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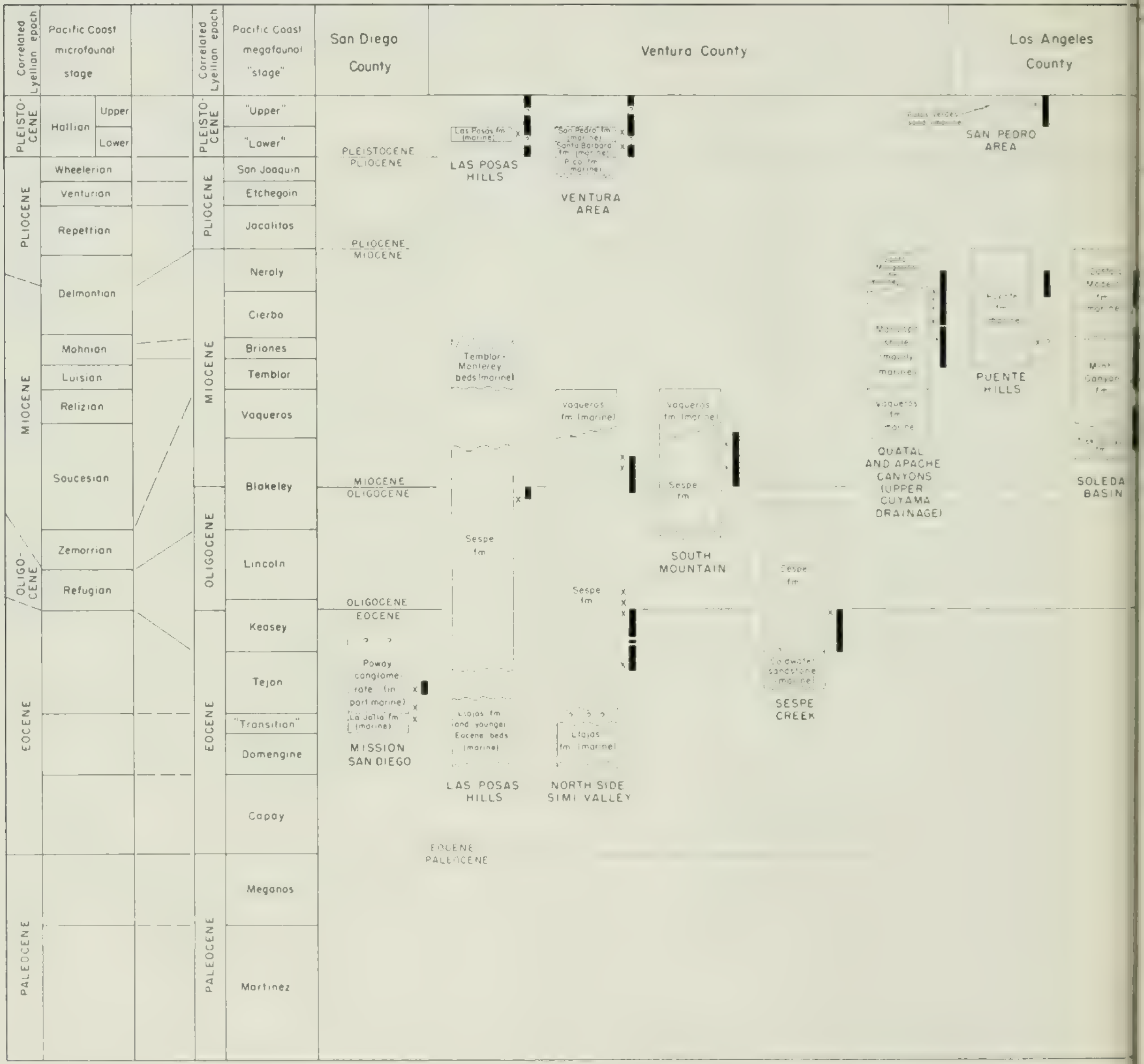
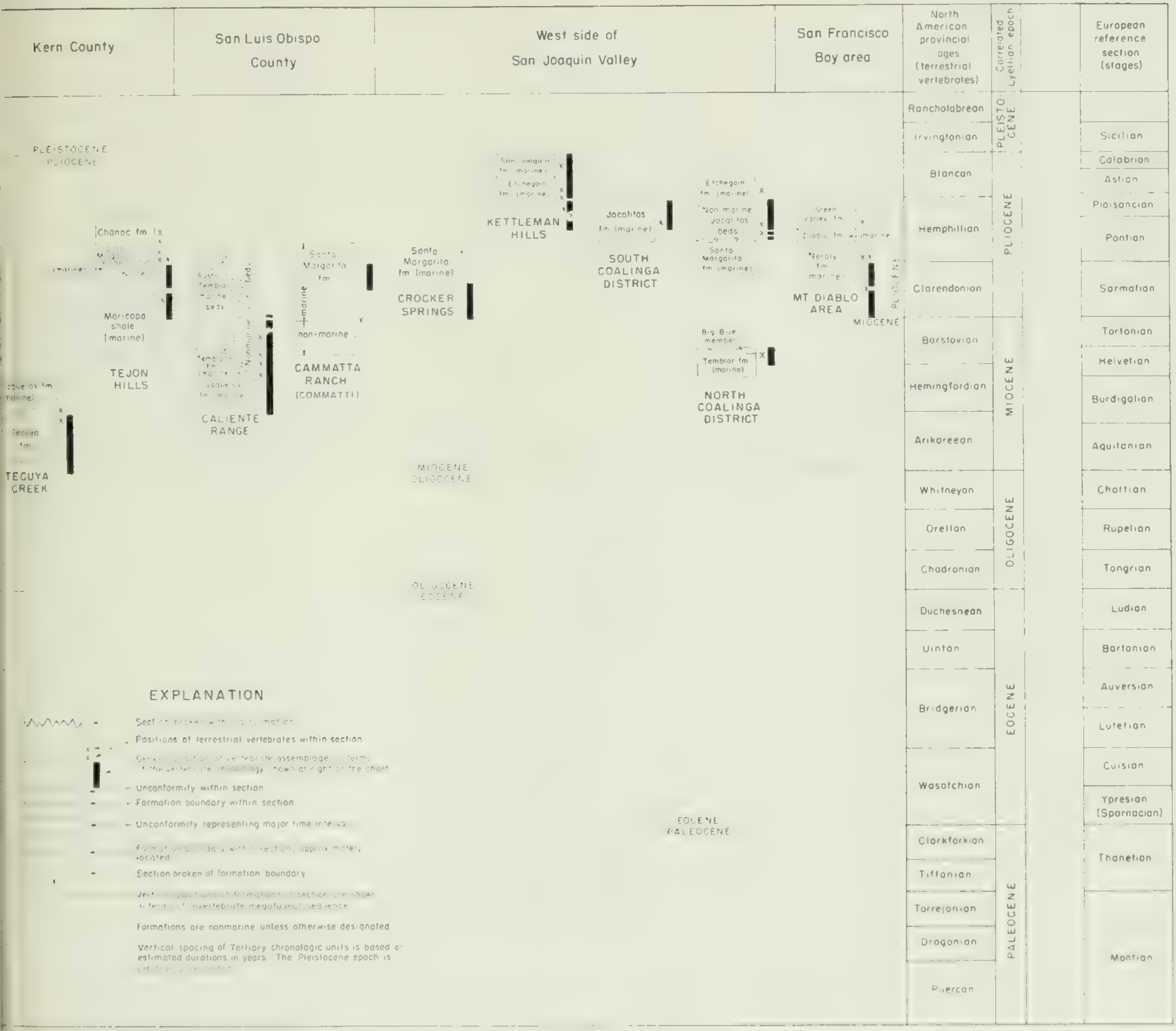


FIGURE 2. Summary of Cenozoic marine-nonmarine relationships in California, showing various correlations of microfaunal, megafauna
Stirton (1951), an



...d terrestrial vertebrate occurrences with the European reference section. Based in part upon data from Weaver, et al. (1944), Simpson (1947), ...hers noted in text.

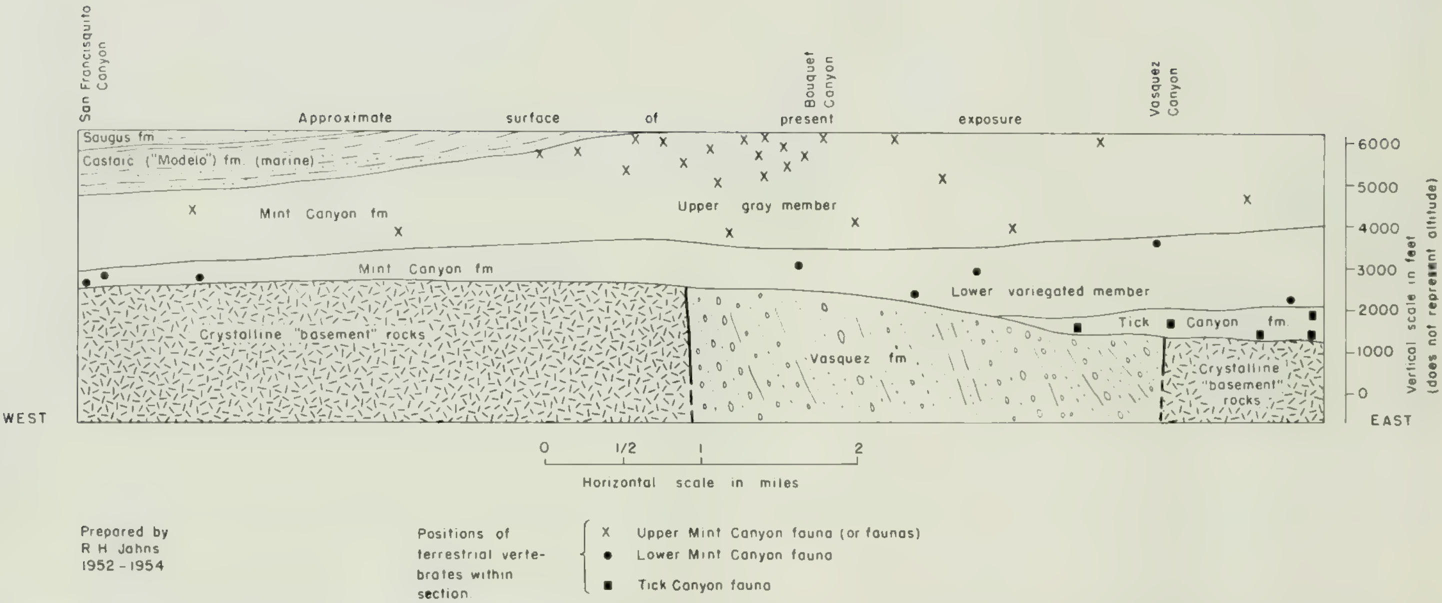

San Francisquito Canyon
Approximate surface of present exposure
Bouquet Canyon
Vasquez Canyon
Saugus fm
Castaic ("Modelo") fm. (marine)
Mint Canyon fm
Upper gray member
Mint Canyon fm
Lower variegated member
Crystalline "basement" rocks
Vasquez fm
Tick Canyon fm.
Crystalline "basement" rocks
6000
5000
4000
3000
2000
1000
0
Vertical scale in feet (does not represent altitude)
WEST
EAST
0
1/2
1
2
Horizontal scale in miles
Prepared by R H Jahns 1952 - 1954
Positions of terrestrial vertebrates within section
X Upper Mint Canyon fauna (or faunas)
● Lower Mint Canyon fauna
■ Tick Canyon fauna

FIGURE 3. Diagrammatic section showing relations of stratigraphic units, vertebrate faunas, and occurrences of specifically identifiable fossils in the Tick Canyon, Mint Canyon, and associated formations of the Soledad basin.

GENERAL FEATURES OF CORRELATION

Two chronologies are now in common use in the Cenozoic marine sections of California. One chronology is based on "metazoans," or more familiarly "megafossils," and has been used as a standard in the correlation chart of Weaver, et al. (1944). This chronology is based on the distribution of megafossil faunas within formations and sequences of formations, and has evolved in a rather haphazard and undisciplined manner. The units within the chronology have been called stages and are based on the faunas of well known and presumably characteristic formations. Each stage is named after the presumed typical formation; thus, for example, the "Vaqueros stage" has been conceived from the "Vaqueros fauna" of the Vaqueros formation.

The other marine chronology is based on distribution of Foraminifera in continuous sections (see, for example, Kleinpell, 1938). The units of this microfaunal chronology also are termed stages, but their names are not based on formational units. The studies leading to the proposal of the various microfaunal stages have all been made within the last 25 years, and have resulted in a carefully disciplined chronology applicable to beds that contain Foraminifera.

The widely used mammalian chronology that has been applied to terrestrial strata in North America comprises basic units that have been termed "provincial ages." These provincial ages have been assigned epochal positions in the Lyellian chronology (i.e., reference to epochs such as Eocene or Oligocene); these positions do not agree in all instances with the epochal positions assigned to correlative intervals on the basis of invertebrate fossil assemblages, and vertebrate paleontologists differ as to the extent of the disagreement. Some lack of correspondence certainly exists, however, and for this reason discrepant age assignments commonly are given to the same formations by the invertebrate and the vertebrate paleontologists, as noted for several California occurrences in the following sections of this paper. When these discrepant epochal assignments are analyzed, however, they may be found to refer to the same "absolute" age. It is to be hoped that, in the future, vertebrate and invertebrate paleontologists can agree on identical boundaries for the Lyellian epochs.

Lyellian dating of Pacific Coast Cenozoic strata involves repeated reference to, and comparison with, the type European sections of the Tertiary as defined by Lyell and Deshayes. This immediately raises certain complications, in part because the types of the various series do not occur in superposition and thus their boundaries are not adequately controlled, and in part because there is disagreement among geologists and paleontologists with respect to the positions and relative ages of vertebrate and invertebrate fossils in certain parts of the European section.

Many investigators believe that the mammalian geochronology, based on the common occurrence of mammalian genera in different continental areas, offers the greatest possibilities for refinement in Cenozoic intercontinental correlations. This view is founded mainly upon the following premises:

1. Mammalian genera that at present are considered significant to intercontinental correlation are characterized by limited chronologic ranges in comparison to similarly widespread genera of other groups of animals in the Cenozoic.
2. Genera of restricted chronologic range are found in both Europe and California.
3. These genera were able to disperse and migrate in a manner relatively independent of environmental control as compared to most other organisms.
4. The critical mammalian genera moved rapidly enough so that the lag of time in their dispersal and the time differential of their appearance on different continents *(homotaxis)* are insignificant in time-stratigraphic terms of stage-age magnitude.

Others argue that inter-continental migrations of mammalian genera can be effectively blocked by narrow marine barriers for epochs of geologic time, and hence that a complete and accurate record of land connections might be critical in evaluating certain differences in mammalian forms on different continents. Knowledge of the geography and chronology of such connections is still far from complete, but points 1 and 2 above would suggest that this difficulty need not be a serious one. It also is argued that the epochal boundaries in the marine section commonly correspond to major episodes of tectonic activity, and hence constitute logical breaks in the sequence, but the available data suggest that this concept is considerably over-simplified.

It cannot be denied that marine invertebrate fossils ordinarily are much more abundant and widespread than terrestrial vertebrate fossils, but this oft-repeated point has little real bearing on the basic problem in a region where fossiliferous marine and nonmarine strata appear in various parts of the same section. In California, for example, there is no lack of marine-nonmarine tie-ins within the upper Miocene-lower Pliocene part of the section, where the most vexing discrepancies between vertebrate and invertebrate dating occur. Thus it should be quite feasible to bring the Lyellian epochs of the marine invertebrate chronology into adjustment with those of the mammalian chronology, especially if paleontologists can reach agreement as to the positions of the epochal boundaries in the type areas of Europe.

It is not the purpose of this paper to recommend specific adjustments between the vertebrate and invertebrate chronologies, but it does seem desirable to indicate the position and magnitude of some of the discrepancies that are known to exist. These are summarized graphically in figure 2, which indicates the stratigraphic and paleontologic relationships in 20 areas of Cenozoic rocks in California.

The vertical positions of the rock units in each area are plotted in accordance with the invertebrate megafaunal sequence, which is shown on the left-hand side of the chart. The occurrences of terrestrial vertebrate fossils within each section are shown as accurately as possible, and the adjacent vertical bars indicate the positions of these assemblages in terms of a vertebrate chronology that is employed by many, though not all, vertebrate paleontologists. This chronology is shown on the right-hand side of the chart. Thus any discrepancy between the invertebrate and vertebrate scales is reflected by a difference between the vertical position of that part of the rock unit in which the vertebrates are found and the position of the bar corresponding to the vertebrate assemblage in question.

Boundaries between Lyellian epochs are indicated by horizontal lines across the chart except in the instance of the Miocene-Pliocene boundary, which is at different levels in the vertebrate and invertebrate sequences that are shown. This conflicting boundary assignment arises because the vertebrate-bearing rocks assigned to the Pontian and Sarmatian of Europe, which commonly are regarded as equivalents of the Hemphillian, Clarendonian, Neroly, Cierbo, and Delmontian (fig. 2), do not occur in the type areas of the Miocene and Pliocene section in Europe and were not included in the type description. Assignment of the Pontian and Sarmatian (or their subdivisions or correlatives) to an epochal position has varied chiefly according to the paleontologic discipline involved. In the mammalian chronology, Pontian and Sarmatian correlatives often have been placed in the Pliocene, whereas in the marine chronologies they generally have been placed in the Miocene by molluscan paleontologists (e.g., Clark, et al., in Weaver, et al., 1944 chart), or have been termed "Mio-Pliocene" or "Miocene-Pliocene" (e.g., Beck, et al., in Weaver, et al., 1944 chart; Kleinpell, 1938) by some micropaleontologists. They also have been regarded as Miocene in continental correlations by some mammalian paleontologists. This purely terminological discrepancy has led to the peculiar situation, noted long ago by Reed and Hollister (1936, pp. 1586-1588), in which "the Lower Pliocene of most vertebrate paleontologists is at least in part the equivalent of the Upper Miocene of the invertebrate paleontologists."

CORRELATIONS IN CALIFORNIA

Poway Conglomerate. The earliest record of land mammals presently known in California is found in the Poway conglomerate and at the top of the underlying Rose Canyon shale of the La Jolla formation (Stock, 1937, 1938a, 1939; Wilson, 1940b), near San Diego (fig. 1). The Poway fauna includes an insectivore, an anaptomorph primate, at least six species of early sciuromorph rodents, a brontothere ("titanothere"), and an amynodont rhinoceros. The total aspect of the assemblage indicates that it is in about the same stage of evolution as the Wagonhound fauna of the Rocky Mountain region, Uintan provincial age (late Eocene), although there are no species in common (except possibly one) between the two areas. Four genera of carnivores are common to Europe and North America in late Eocene time, but none of these has yet been found in the Poway beds; hence, no direct comparison with Europe is possible. The Poway fauna must be compared with the early faunas of the Sespe formation or with the Uinta faunas, which in turn are suggested to be contemporaneous with the European mammals reported to represent the Bartonian or Ludian stages. The position of the Poway mammals with respect to the invertebrates recorded from the formation by Hanna (1927b), Dusenbury (1932), and Cushman and Dusenbury (1934) is not clear, but examination of Hanna's map (1927a) would suggest that the brontothere was obtained from about the same stratigraphic position as Dusenbury's faunule. On the basis of the meager data now available, the relative stratigraphic positions of the other mammal occurrences are uncertain.

According to the chart in Weaver, et al. (1944), as well as the investigators listed above, the marine fossiliferous part of the Poway conglomerate is to be correlated with the Tejon stage. This is about early upper Eocene in local terminology, and is considered equivalent to the Bartonian stage of Europe as shown in the Weaver chart. Cushman and Dusenbury (1934) also correlate their foraminiferal faunule with the upper Claiborne faunas of the Gulf Coast. According to the correlation chart of the Gulf Coast region (Cooke, et al., 1943), the upper Claiborne is about equivalent to the Auversian stage (next older stage than Bartonian) of Europe. On the other hand, the middle Claiborne has yielded a titanothere of late Uintan to Duchesnean type (Gazin and Sullivan, 1942), which raises some complications (fig. 2). It would appear that there is general but not precise agreement that the age of at least a part of the Poway conglomerate is about early upper Eocene.

Sespe Formation. The Sespe formation, which is widely distributed in parts of the Transverse Range and Peninsular Range provinces of southern California, has yielded vertebrate faunas of several different ages. The Tapo Ranch faunas of Stock (1934a, b, c) and Wilson (1940a, c; 1949a, c) are contained in the lower half of the 7,400 feet of sediments referred to the Sespe in the Simi Valley area (fig. 2), and mammals of this fauna occur between 1,830 feet and 3,270 feet above the base of the formation (Stock, 1932a). Here the nonmarine Sespe section is reported to be separated from the underlying marine Llajas formation by an erosion interval (Stock, 1932a), but in places the two formations appear to be conformable (Stipp, 1943). According to Laiming (1941), the youngest marine beds of the Llajas are to be referred to his B-1A zone, which is either late Domengine or "Transition" age in the megafaunal sequence.

The Tapo Ranch fossil vertebrates constitute the earliest mammalian assemblage known from the Sespe formation, and are considered to be of about the same age or a little younger than the Poway fauna. Two faunal stages are recognized (Stock, 1934a, p. 150; 1934b, p. 349) from the fossiliferous part of the Tapo Ranch section. A part of the assemblage is Uintan (late Eocene), and is thought to be contemporaneous with the Myton fauna (Uinta C) of Utah. Species of *Viverravus* and *Miacis*(?), two carnivores, offer a means of comparison with species of these genera reported from deposits of the Ludian stage, from the type area of the Eocene in France, although the Ludian may be younger than Uintan. A distinctly younger part of the assemblage seems to correspond to the fauna from deposits that overlie the Upper Uinta (Uinta C) strata of the Uinta Basin (Stock, 1932a, p. 523; 1934e, p. 625), and hence is probably Duchesnean (latest Eocene).

Although the position of this uppermost Eocene fauna is compatible with that of the invertebrate fauna of the underlying marine strata, complications with respect to the Duchesnean are recognized in other regions. As pointed out by G. E. Lewis (personal communication), *Notiotitanops*, a titanothere found *in situ* in the Lisbon formation of the middle Claiborne group in Mississippi, is closer to *Teleodus* of the Chadron and Duchesne River assemblages than to any other genus, although there are resemblances to *Diplacodon*, *Protitanotherium*, and *Eotitanotherium* of the Uinta (Gazin and Sullivan, 1942). The marine Lisbon formation, however, is generally regarded as a correlative of the Lutetian stage, or distinctly older in terms of the European reference section (fig. 2).

The upper part of the Sespe section on the north side of Simi Valley has yielded a sparse vertebrate fauna that includes *Archaeolagus*(?) and a leptauchenid (Wilson, 1949b). These forms, which are regarded as Arikareean (early Miocene) in age, occur stratigraphically below an interfingering contact between the Sespe strata and overlying marine Vaqueros strata (fig. 2), and hence are in reasonably good agreement with the mega-invertebrate chronology.

Stock (1938b) described *Teleodus*, a brontothere, from the type Sespe formation of Sespe Creek, north of Ventura (fig. 1). This specimen is dated as Duchesnean (latest Eocene), and it was found 400 feet to 700 feet above the Coldwater sandstone (fig. 2). The paleontological collections of the University of California contain specimens of *Turritella uvasana sargeanti* from the Coldwater strata on Santa Paula Creek, indicating a Tejon age, but Clements (1943) and others have stated that the Sespe formation rests unconformably on the Coldwater sandstone. Thus evaluation of the age relationships is somewhat uncertain, except that the Sespe of the type area is younger than the Coldwater sandstone.

In the South Mountain area, about 20 miles southeast of the type Sespe area, a few mammals have been found in the Sespe formation between 400 and 2,000 feet beneath its contact with the conformably overlying marine Vaqueros formation. These mammals include oreodonts and rodents (Stock, 1934d), and are considered to be of probable Arikareean age (early Miocene). The overlying Vaqueros formation in this area is considered to represent the "lower" Vaqueros by Loel and Corey (1932, correlation table).

Fossil vertebrates also have been obtained from the upper part of the Sespe formation in the Las Posas Hills, approximately 6 miles south-southeast of the South Mountain area (fig. 1). An erosional break separates the terrestrial beds from overlying marine strata of Miocene age (fig. 2). The fauna, which is large and includes much relatively complete material, is wholly different from the other Sespe faunas (Stock, 1933a, b, 1935c; Wilson, 1949b). The rhinoceroses, horses, camels, carnivores, rodents, and other forms are represented, but oreodonts are absent. Although the fauna can be correlated in a general way with that from the lowest fossiliferous beds of the Sespe formation at South Mountain (Stock, 1934d, p. 523), it appears to be Whitneyan (late Oligocene), rather than Arikareean (early Miocene), in age (Stock, 1933a, pp. 26-27; 1933b, p. 31; Wilson, 1949b, p. 63).

Tecuya Formation. At Tecuya Creek, about 40 miles north of the South Mountain area (fig. 1), a fauna of Arikareean age occurs in red beds of the Tecuya formation on the north side of the Tehachapi Mountains (Stock, 1920, 1932e). The fauna includes squirrel, rhinoceros, oreodont, dog, and a small deer-like animal. According to the available evidence, the Tecuya beds both underlie and interfinger with strata of the Vaqueros formation (fig. 2). Loel and Corey (1932, correlation table) regard the Vaqueros formation of this area as considerably younger than the basal Vaqueros at South Mountain, and consider it to represent their "upper" Vaqueros.

Thus in two places, South Mountain and Tecuya Creek, terrestrial beds that lie beneath the Vaqueros formation are dated as lower Miocene in the vertebrate chronology, although it is well to note that the Aquitanian stage of Europe, with which the lower Arikareean is correlated (Simpson, 1947), is not contained in Lyell's type Miocene, and that it has been considered as part of the upper Oligocene by some investigators. If the vertebrate evidence is significant, it would appear that the Vaqueros "stage" must be at least in part a correlative of the upper Aquitanian or perhaps even the lower Burdigalian of Europe. This contrasts with the correlation indicated for the "micro" classification in the chart of Weaver, et al. (1944), where the Vaqueros is indicated as being at least in part as old as the Rupelian stage of Europe.

Nonmarine Beds of the Caliente Range. From the Caliente Range, near the southeast corner of San Luis Obispo County (fig. 1), Dougherty (1940) has described land mammals that occur in a thick section of nonmarine beds. After detailed study of the intergrading relationships between marine and nonmarine sediments in this area, he concluded that the fossiliferous beds are at the same or at a slightly lower stratigraphic level than rocks corresponding to the upper part of the Relizian stage, and that they are to be correlated with the uppermost type Temblor formation and with a part of the overlying Gould shale (fig. 2). Much of the mammalian assemblage described by Dougherty is characteristic of Hemingfordian (mid-Miocene) faunas, but other parts of the assemblage may be Barstovian (late Miocene) or younger. Indeed, the antilocaprid found highest in the section at Padrones Spring (Calif. Inst. Tech. Loc. 170 and Univ. California Mus. Paleo. Loc. V2704) is a type that might be dated as not older than Clarendonian (early Pliocene). The nonmarine sediments of the Caliente Mountains area appear to represent a large span of later Cenozoic time (fig. 2), and the vertebrate assemblages may represent two or more distinct faunas, each of which can be correlated with a different part of the marine section (Eaton, Grant, and Allen, 1941, p. 230). It is clear that this area of marine and terrestrial sediments offers interesting stratigraphic problems for future study.

Mint Canyon and Tick Canyon Formations. The Mint Canyon formation of the Soledad basin, in northwestern Los Angeles County (fig. 1), has been the major focal point in southern California about which controversy over the Miocene-Pliocene boundary has swirled. The difficulties have stemmed in part from a discrepancy between the invertebrate and some of the vertebrate chronologies, as noted in a foregoing section of this paper, and in part from interpretations based upon vertebrate faunas whose stratigraphic positions were imperfectly known. A detailed study of some of the nonmarine strata in the Soledad basin (Jahns, 1940) demonstrated that a well-defined fauna, comprising forms distinctly older than all the others known from the section, represents the lowermost beds of the Mint Canyon formation as originally defined by Kew (1924, pp. 52-54). This fauna comprises rodent, horse, camel, and oreodont remains of Arikareean and possibly earliest Hemingfordian age (fig. 2), and the beds in which it occurs are now included in the Tick Canyon formation, which is separated by a slight erosional break from the overlying Mint Canyon formation as redefined (Jahns, 1940, pp. 163-166).

Further study has shown that at least two distinct vertebrate faunas are present in the Mint Canyon formation as now restricted. The older of these is in large part undescribed, so far as the published record is concerned. It occurs in the lower one-fourth to one-half of the formation, which is characterized by relatively fine-grained and variegated strata (fig. 3). Fossil material from the Bouquet Canyon and San Francisquito Canyon areas includes representatives of the horses, rhinoceroses, camels, antelopes, and carnivores, and corresponds very closely to the assemblage from the Barstow formation of the Mojave Desert region. Thus the lower part of the Mint Canyon formation is Barstovian, or late Miocene, in age (fig. 2).

The younger mammalian material in the Mint Canyon formation, which occurs in an upper sequence of coarse-grained, prevailingly light-colored strata (fig. 3), may comprise two faunas of differing ages. It includes a *Hipparion* very similar to a well-known species from the Ricardo fauna of the Mojave Desert region. This is a horse with higher-crowned teeth as compared to *Merychippus* of the Barstow formation. Largely on the basis of this horse, the upper part of the Mint Canyon formation is dated by many vertebrate paleontologists as later Clarendonian (early, but not earliest Pliocene of the mammalian chronology). Other vertebrate paleontologists, in contrast, regard this occurrence as representing the first appearance of *Hipparion* in North America during Barstovian (late Miocene) time, whence the genus migrated to Europe. In Europe the genus first appears in strata of the Sarmatian stage, which is regarded by these same investigators as latest Miocene in age.

The Mint Canyon strata are overlain with distinct angular unconformity by the marine Castaic formation (Winterer and Durham, Eastern Ventura basin Map Sheet, this volume), the Modelo(?) or "Modelo" formation of earlier investigators. These marine beds contain molluscan, echinoid, and foraminiferal faunas that have been dated as of probable "Cierbo" age in part and as of "Neroly" age in the megafaunal sequence, and in part as of Mohnian age in the microfaunal sequence (Durham, 1948; White and Buffington, 1948; Wright, 1948). In both marine classifications the assigned ages are referred to the upper Miocene.

These relations point up a serious discrepancy between the invertebrate chronology and the vertebrate chronology that is favored by many paleontologists (fig. 2), a discrepancy that can be resolved only by agreement among paleontologists as to the formational and faunal successions, which is fundamental to correlation of these chronologies with the Lyellian epochs. The problem is summarized in figure 4, in which the positions of the Mint Canyon formation and overlying marine strata are plotted, according to each of the chronologies, with respect to a horizontal line denoting the Miocene-Pliocene boundary.

Puente Formation. Somewhat similar problems of dating are posed by occurrences of fossil mammals in the marine Puente formation of the Puente Hills, in southeastern Los Angeles County (fig. 1). These scattered remains include *Hipparion*, and may occur in strata that contain a lower Mohnian microfauna. There appears to be some doubt, however, as to the true stratigraphic relationships of the only definitive vertebrate material, a horse tooth.

Maricopa Shale. A thick section of Maricopa shale, in which fossiliferous nonmarine strata are present, is well exposed in Quatal and Apache Canyons, in the upper part of the Cuyama River drainage near the northwest corner of Ventura County (fig. 1). The vertebrate assemblage includes horses, oreodonts, a camel, a mastodont, a carnivore, rodents, and birds, and in part appears to be of Barstovian age. It is distinctly younger than the fauna of the Tecuya formation, and perhaps is in part of the same age as the Barstovian fauna from the Mint Canyon formation (Gazin, 1930, p. 63). On the other hand, some of the forms appear to be of Clarendonian age, and it seems best to divide the known vertebrate assemblage into two distinct faunas (C. L. Gazin, personal communication). Further stratigraphic study of the fossil occurrences might well disclose relations similar to those of the Mint Canyon formation.

The Maricopa shale is underlain by the marine Vaqueros formation (fig. 2), and is overlain unconformably by marine "Santa Margarita" strata of late Miocene age. Marine beds within the Maricopa section permit dating of the vertebrate-bearing strata as Temblor (Gazin, 1930, p. 61) or slightly younger. Thus a Barstovian age for the vertebrate-bearing strata is reasonably compatible with the age indicated by the megafaunal invertebrate sequence, but a younger age assignment for some of the veterbrate remains once again would raise the Miocene-Pliocene boundary problem that already has been discussed.

Santa Margarita and Chanac Formations. Vertebrate fossils occur beneath the marine part of the "Santa Margarita" formation in the Comanche Point area of the Tejon Hills, south-southeast of Bakersfield (fig. 1). Four miles south-southeastward, a slightly older assemblage (the lower fauna of Tejon Hills) is present in beds that also are regarded as nonmarine parts of the "Santa Margarita" section. This older fauna has been interpreted as latest Miocene in age by some investigators (e.g., Drescher, 1941, p. 8), and as Clarendonian in age by others (e.g., Stirton, 1939a). Marine fossils from the "Santa Margarita" strata (Nomland, 1917, p. 302) indicate a Neroly age in the megafaunal sequence, and thus the relations of the vertebrate and invertebrate chronologies correspond, in general, to those in the Mint Canyon area.

The younger fauna, from strata beneath marine beds of the "Santa Margarita" formation, appears to be Clarendonian in age (Durham and Savage, 1954). A third, still younger, fauna has been obtained from the conformably overlying beds of the Chanac formation, and is of later Clarendonian age (fig. 2).

At Cammatta (Commatti) Ranch, on the Highland monocline about 20 miles southeast of Paso Robles (fig. 1), a vertebrate fauna has been obtained from what appears to be an interval just below the base of the marine Santa Margarita formation. This fauna is Clarendonian in age (Durham and Savage, 1954), whereas the age of the associated marine strata would approximately correspond to the boundary between the Mohnian and Delmontian stages of the microfaunal sequence (Kleinpell, 1938, fig. 6).

The occurrence of the fossil dog *Osteoborus* in the marine Santa Margarita formation at Crocker Springs (VanderHoof, 1931; Barbat and Weymouth, 1931), on the west side of the San Joaquin Valley (fig. 1), is thought by many vertebrate paleontologists to suggest an early Clarendonian age. These strata would be regarded as upper Miocene in terms of the invertebrate chronology.

Neroly Formation. The marine Neroly formation, on the west side of Mount Diablo in the San Francisco Bay region, yields fossil remains of the horse *Nannippus tehonensis* (Merriam). This indicates an early Clarendonian age (Stirton, 1939b, p. 350). A few miles southeast along the strike from the Neroly occurrence and about 2,000 feet higher stratigraphically, the well-preserved Black Hawk Ranch mammalian fauna (Macdonald, 1948; Richey, 1948) from the continental Green Valley formation indicates a later Clarendonian age, and may be in general correlative with the upper fauna of the Mint Canyon formation (fig. 2). It will be recalled that this upper Mint Canyon fauna is from beds that lie unconformably *beneath* the marine correlative of the Neroly and Cierbo formations. This discrepancy in marine and nonmarine correlations between central and southern California is one of the outstanding problems of current stratigraphic interpretations in the State.

Strata of the Coalinga-Kettleman Hills Area. In the North Coalinga district (fig. 1), northwest of Tulare Lake and about half-way up the west side of the San Joaquin Valley, abundant vertebrate remains have been taken from a locality known as the *Merychippus* quarry (or *Merychippus* "zone"). The fauna contains four canine genera, one species of rodent, two species of *Merychippus* (a grazing-browsing horse), three other species of horses, a rhinoceros, a mastodont, a peccary, a cervid, and three species of camels (Merriam, 1915; Bode, 1934, 1935). The genera relative to which this assemblage could be compared directly with mammals from the Miocene series of Europe are the mastodont, *Amphicyon*, *Hemicyon* ?, and *Monosaulax* (G. E. Lewis, personal communication), but thus far the dating of this fauna has been based exclusively on the evolutionary advancement of the exclusively North American merychippine horses relative to the horses in other, more complete, North America faunas. On this basis the North Coalinga site is believed to be Barstovian (late Miocene) in age, possibly early Barstovian. The quarry is a short distance stratigraphically above the "Button Bed" of the marine Temblor formation, and thus corresponds either to the upper Relizian stage or about to the boundary between the Relizian and Luisan stages (mid-Miocene of the mircofaunal classification). It is at the top of the Temblor formation and "stage" (mid-Miocene of the megafaunal classification). Here, therefore, there is little discrepancy of dating between the terrestrial and marine classifications.

Terrestrial vertebrates are known from both marine and nonmarine strata elsewhere in the North Coalinga district (fig. 2). The horse *Pliohippus coalingensis* (Merriam) was found about midway in the type section of the marine Jacalitos formation by W. P. Popenoe (unpublished data), and in the so-called "nonmarine Jacalitos" beds as well as in the overlying marine Etchegoin strata northeast of Coalinga (Nomland, 1916). The horse *Neohipparion molle* (Merriam) also was found in the "nonmarine Jacalitos." The Jacalitos formation is conventionally considered to be lower Pliocene in the marine chronology based on mollusca and echinoids, whereas the horses would indicate a later Hemphillian age (late mid-Pliocene) in the terrestrial mammalian chronology of many paleontologists.

Woodring, Stewart, and Richards (1941, p. 98) cite the occurrence of horse teeth in the *Siphonalia* and *Patinopecten* "zones" of the Etchegoin formation of the Kettleman Hills district. These teeth were identified by Stock as belonging to the genus *Pliohippus*, and were thought by him and others to indicate a Clarendonian age in terms of the mammalian chronology. It seems possible, however, that the teeth could as well represent a horse of Hemphillian age (middle Pliocene). The Etchegoin formation is considered to be middle Pliocene in the marine sequence, also (Weaver, et al., 1944).

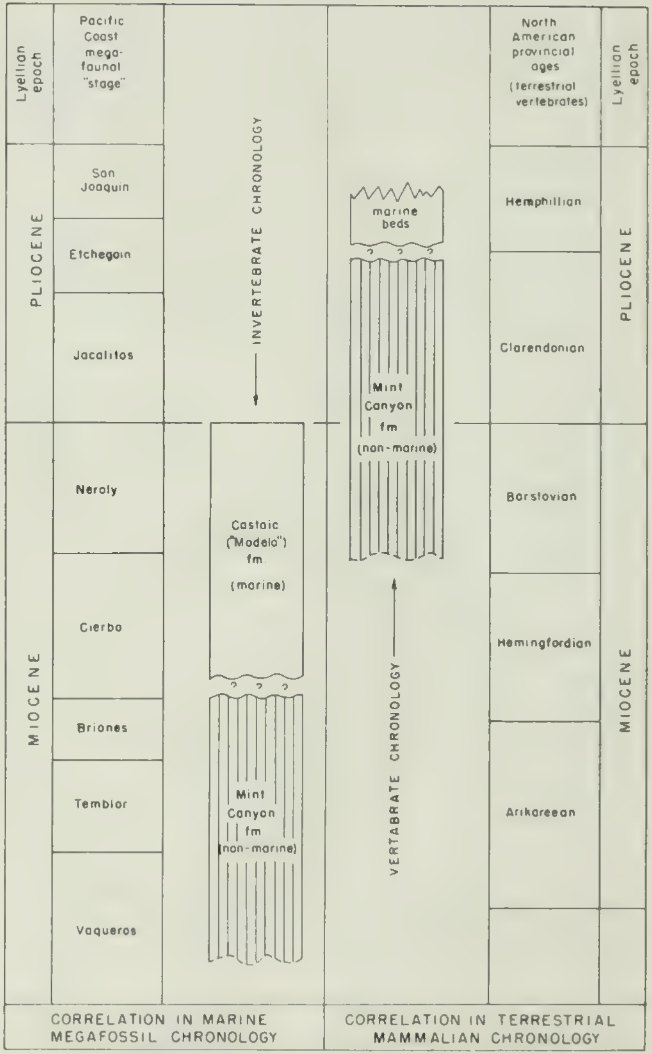

Lyellian epoch
Pacific Coast mega-faunal "stage"
PLIOCENE
San Joaquin
Etchegoin
Jacalitos
MIOCENE
Neroly
Cierbo
Briones
Temblor
Vaqueros
INVERTEBRATE CHRONOLOGY
Castaic ("Modelo") fm (marine)
? ? ?
Mint Canyon fm (non-marine)
marine beds
? ? ?
Mint Canyon fm (non-marine)
VERTABRATE CHRONOLOGY
North American provincial ages (terrestrial vertebrates)
Hemphillian
Clarendonian
Barstovian
Hemingfordian
Arikareean
Lyellian epoch
PLIOCENE
MIOCENE
CORRELATION IN MARINE MEGAFOSSIL CHRONOLOGY
CORRELATION IN TERRESTRIAL MAMMALIAN CHRONOLOGY

FIGURE 4. Chart showing discrepancy between vertebrate and invertebrate chronologies, as applied to the upper part of the Mint Canyon formation and to the overlying marine strata. Positions of the stratigraphic units are plotted, on the basis of the respective chronologies, with reference to a horizontal line that denotes the Miocene-Pliocene boundary.

The San Joaquin formation is the uppermost of the more purely marine units in the San Joaquin Valley. Customarily it has been referred to the upper Pliocene (Woodring, 1952) in both the marine and nonmarine chronologies of the Pacific Coast. It is to be noted, however, that if the vote of the last International Geological Congress (1948) to place the beginning of the Pleistocene epoch at the beginning of the Calabrian (marine) = Villafranchian (nonmarine) stage (Moore, 1949) is followed, the San Joaquin formation probably can be regarded as basal Pleistocene, because it can be referred to the Blancan provincial age of the North American mammalian chronology, at least part of which in turn can be correlated in a general way with the Villafranchian stage of Europe. Mammals found in the San Joaquin strata (Woodring, Stewart, and Richards, 1941, pp. 97-98) include camels, peccaries, *Equus (Plesippus)*, *Castor* (beaver), *Odocoileus* (deer), and Pliomastodon. The horse is very similar to European species from deposits termed Villafranchian or Astian by different authors. These deposits include strata in the type area of the Pliocene series.

Strata of Quaternary Age. The name "*Equus* cf. *occidentalis*" has been applied to numerous isolated bones and tooth fragments obtained from beds called San Pedro or Las Posas (Bailey, 1943; Pressler, 1929; Woodring, 1952), and this name even has been cited as characteristic for the equid material in formations of post-Pleistocene age in the succession of the Los Angeles area (Natland, 1953). The name *Equus occidentalis* has come to mean a large horse comparable to that found in the Rancho La Brea tar pits, but most of the specimens concerned could be referred to any of the larger species of *Equus*. The frequent application of this name to specimens that actually are indeterminable has given to it a halo of preciseness and chronological specificity that is wholly synthetic. As pointed out by Savage (1951), one of the two type teeth of this species was obtained from deposits of Blancan (late Pliocene) age in Kern County, and the other was obtained from gravels in the Sierra Nevada at an unspecified locality in Tuolumne County. Topotype material from the Kern County locality indicates a Blancan age. According to Woodring (1952), the Santa Barbara formation, the San Pedro formation of Bailey, the Las Posas formation, and the type San Pedro formation are all of a Pleistocene age younger than the San Joaquin formation.

Insofar as known mammalian remains are concerned, the complex of intergrading formations that have been termed Saugus, Santa Barbara, San Pedro, and Las Posas in the Ventura basin, the Los Angeles basin, and in border areas probably range in age from Blancan (late Pliocene) through Irvingtonian (earlier Pleistocene), and perhaps through Rancholabrean (later Pleistocene). The evidence thus far marshalled, however, is purely suggestive.

One of the youngest marine-nonmarine "tie-ins" in southern California occurs in the Palos Verdes sand in San Pedro, at the Lumber Yard locality of various writers (Woodring, Bramlette, and Kew, 1946, p. 86). Here a Rancholabrean (later Pleistocene) age is indicated by the presence of *Bison* and species of smaller mammals that still survive in the area. The Palos Verdes sand is considered to be no older than late Pleistocene by practically all paleontologists (Woodring, 1952, pp. 405-406, fig. 1), no matter what criteria are used. The terrace on which this deposit occurs is the lowest of 13 upper Pleistocene marine terraces that are present in the Palos Verdes Hills.

Summary. As indicated in figure 2 and in the foregoing paragraphs, discrepancies between invertebrate and some vertebrate correlations are present at many localities in California where both marine and nonmarine strata are juxtaposed or show interfingering relations. This is scarcely surprising when it is recalled that the terrestrial vertebrate chronology and the marine megafaunal and microfaunal chronologies have been established more or less independently on the basis of relations in widely scattered areas, very few of which include localities discussed in this paper. The most serious of the discrepancies involves the interval upper Miocene—lower Pliocene, and involves problems of faunal and stratigraphic correlation, as well as some purely terminologic difficulties.

At the present time, the available evidence is not adequate to resolve many of the difficulties in correlation and dating, but the following possibilities should be considered:

1. The indicated correlations of any or all of the three chronologies with the European reference section may be incorrect.
2. The time spans of some units in any of the chronologies may be greater than is ordinarily estimated.
3. Many fossils now considered to be time-stratigraphic indices are not such, but instead are only facies indicators.
4. The time span involved in dispersal of faunas, or certain critical members of faunas, may be greater than is currently recognized.
5. Some of the European reference stages may be facies of other stages rather than sequential to them (cf. Gignoux, 1943, and Movius, 1949).
6. The stratigraphic relations between terrestrial vertebrate-bearing strata and marine invertebrate-bearing strata may be incorrectly reported or imperfectly understood in some areas.

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8. TERTIARY BASINS OF SOUTHERN CALIFORNIA

By William H. Corey [*]

Presented in this paper are seven paleogeographic maps, a paleostructural outline map, and a correlation-transgression chart for a part of the southern California region. These have been prepared to improve understanding of the extremely complex Tertiary structure and stratigraphy of the region, and represent an attempt to outline patterns of topography and sedimentation during several critical stages in its varied history. They are the results of accumulation and coordination of data during 27 years of field, laboratory, and office studies of stratigraphic formations and facies in southern California.

No single individual could study and correlate all the sections on which these maps and chart are based, and the writer gratefully acknowledges the generous help of many other investigators. These include members of oil-company staffs, and especially the staff of the Continental Oil Company, as well as authorities from academic institutions and State and Federal surveys.

In the construction of the paleogeographic maps, precise correlations were regarded as the most important factor and were given exhaustive study. Stratigraphic columns were prepared for each major seaway area, and were correlated in greatest possible detail on regional charts. All possible means of correlation were used, and were coordinated on these charts with the help of all available known authorities. Thus each correlation used is best considered as a consensus of opinions. Known occurrences of strata of Paleocene and Eocene, Oligocene, earliest Miocene, later early Miocene, middle Miocene, late Miocene, and Pliocene age were plotted on maps, and symbols were used to distinguish marine and nonmarine conglomerates, sandstones, and shales. Based on the types, relationships, and distribution of these facies, probable general areas of erosion and deposition at corresponding times were plotted on the maps.

A map showing the general distribution of older rocks and the major structural framework of the region was prepared to furnish the necessary background for interpretation of the principal episodes of Tertiary history. Both this map and the paleogeographic maps (figs. 1-8) reflect three basic concepts:

1. Areas of post-Eocene erosion and deposition have been uplifted and depressed mainly by block faulting of the basin and range type, which in general began during Oligocene time and continued intermittently through the Tertiary period.
2. Many blocks have reversed their relative vertical positions along these fault zones, and some blocks have moved many miles laterally along them.
3. Episodes of deformation, erosion, and deposition in all parts of a given block have been similar or closely related.

The probable borders between high areas, in which erosion was dominant, and low areas, in which deposition was dominant, were outlined on the maps for the seven parts of the Tertiary period noted above, and the probable maximum extent of the sea was indicated on each of the maps. In general, it was assumed that at any given time the pattern of erosion and deposition was determined by the relative vertical and horizontal positions of the moving blocks, and that most of the borders or shore lines of depositional basins were controlled, at least in a broad way, by the faulted margins of the blocks. Also significant was the stage of regional uplift or subsidence at a given time. It was found very helpful, both as a check and as a source of additional clues, to work back and forth between the general map (fig. 1) and the paleogeographic maps, and to work forward and backward in time between successive paleogeographic maps. Absence of deposits of a given stage from a considerable part of a block ordinarily was taken to indicate that none were laid down there. The outlines of Tertiary topography and sedimentation in the area that is now submerged are of course more conjectural than those in the area that is now onshore.

It should be pointed out that the effects of thrust faulting in the northwestern part of the area shown in figures 1-8 have been minimized or eliminated by restoration of the rocks to their presumed respective positions prior to the faulting. This has not been done, however, in the case of other faults with strike-slip, or lateral, movements, as definitive information concerning the direction and magnitude of slip is not available for most of these faults. It should be kept in mind, therefore, that lateral adjustments of considerable magnitude might well be required for accurate restoration of geography during the Tertiary period (see Hill, Contribution No. 1, Chapter IV). Finally, it should be noted that the faults in figures 2-8 are shown as they now exist, and therefore they must be regarded, in the strictest sense, as elements of the modern base map on which the paleogeographic data have been plotted.

This study shows that the pattern of topography and sedimentation in the southern California region changed considerably from time to time during the Tertiary period. Broad land and sea features of Eocene time were broken up by regional emergence with block faulting during Oligocene time, but the general plan lasted into early Miocene time, when regional submergence began. Marine transgression continued with few interruptions through Miocene time, and

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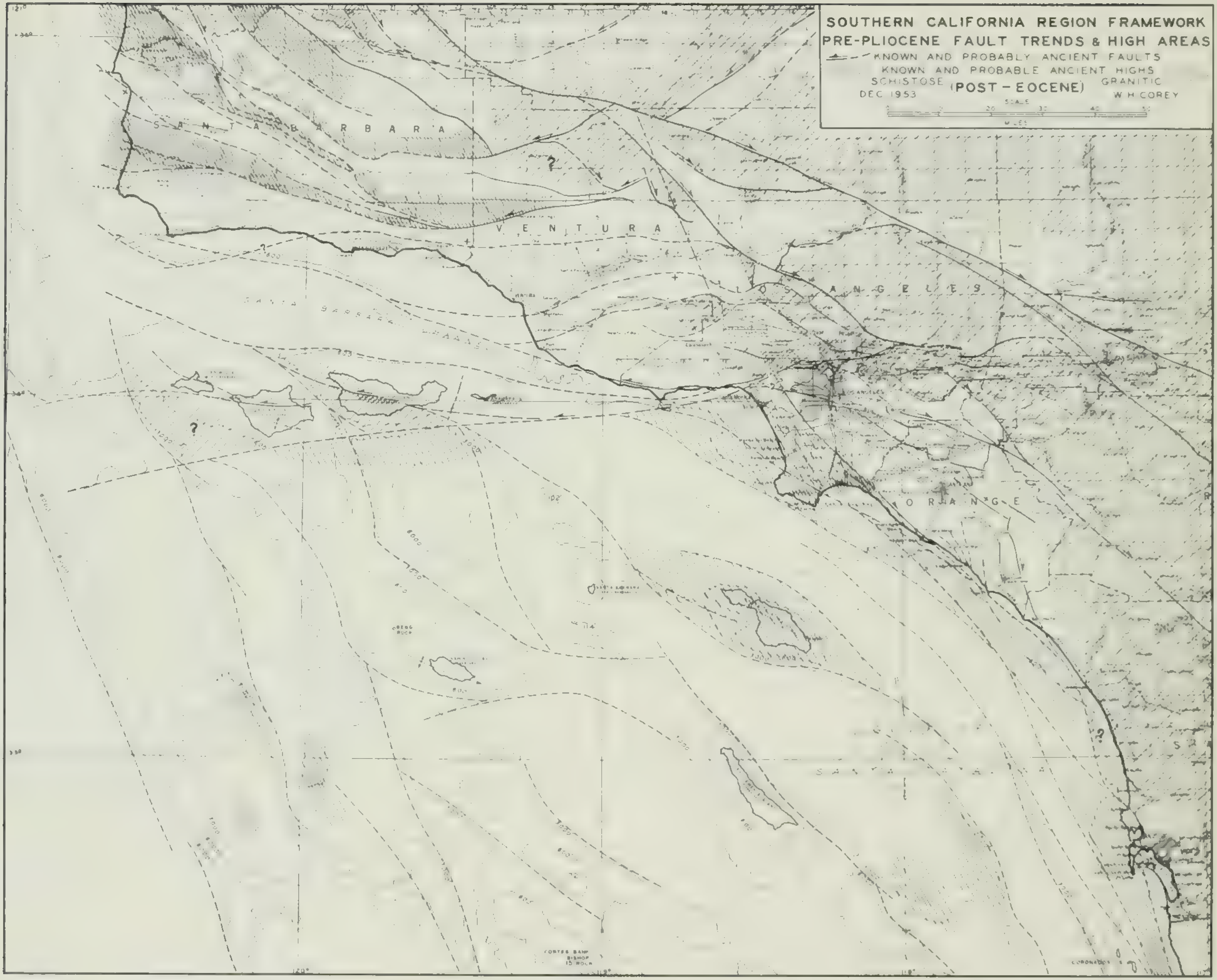
[*] Research Geologist, Western Region, Continental Oil Company.


SOUTHERN CALIFORNIA REGION FRAMEWORK
PRE-PLIOCENE FAULT TRENDS & HIGH AREAS
KNOWN AND PROBABLY ANCIENT FAULTS
KNOWN AND PROBABLE ANCIENT HIGHS
SCHISTOSE
(POST – EOCENE)
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W.H. COREY
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MILES
SANTA BARBARA
VENTURA
LOS ANGELES
ORANGE
SANTA BARBARA CHANNEL
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?
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FIGURE 1. Map of a part of southern California, showing the regional framework of post-Eocene pre-Pliocene fault trends and Tertiary highland areas of older rocks. The fault trends are necessarily generalized, especially in the present offshore area.
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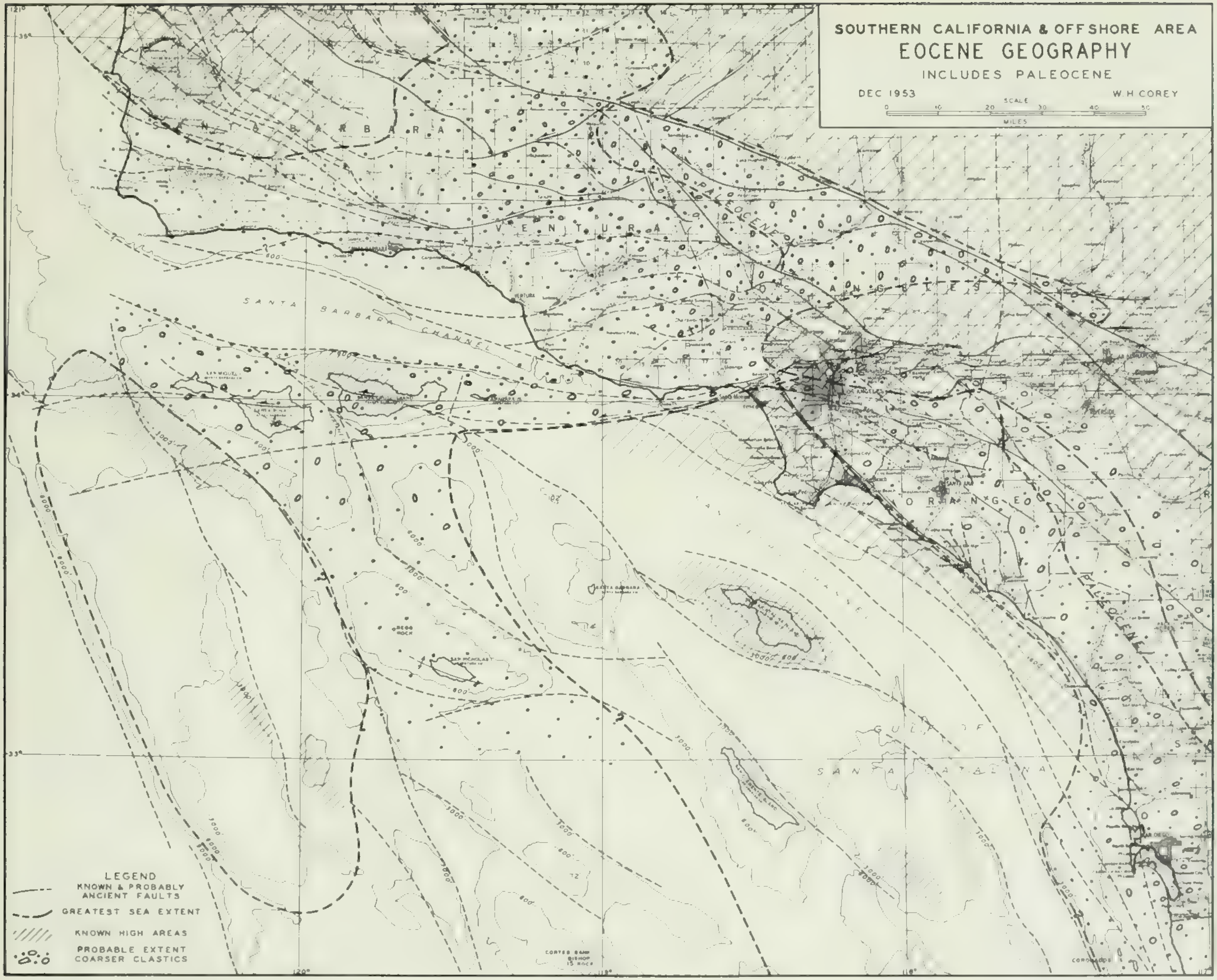

FIGURE 2. Map of part of southern California, showing general geography and pattern of sedimentation in Paleocene and Eocene time.

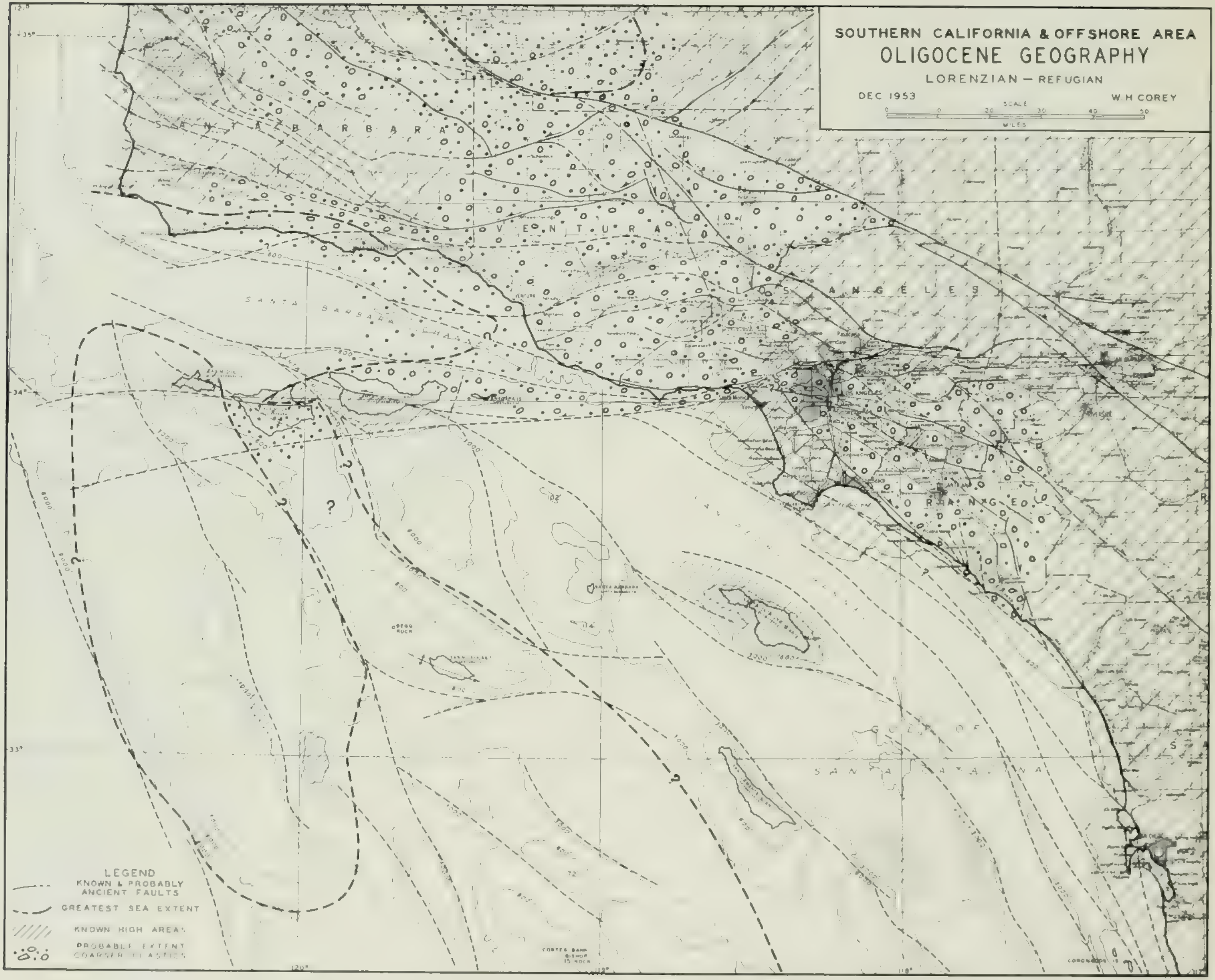

FIGURE 3. Map of a part of southern California, showing general geography and pattern of sedimentation in Oligocene time.

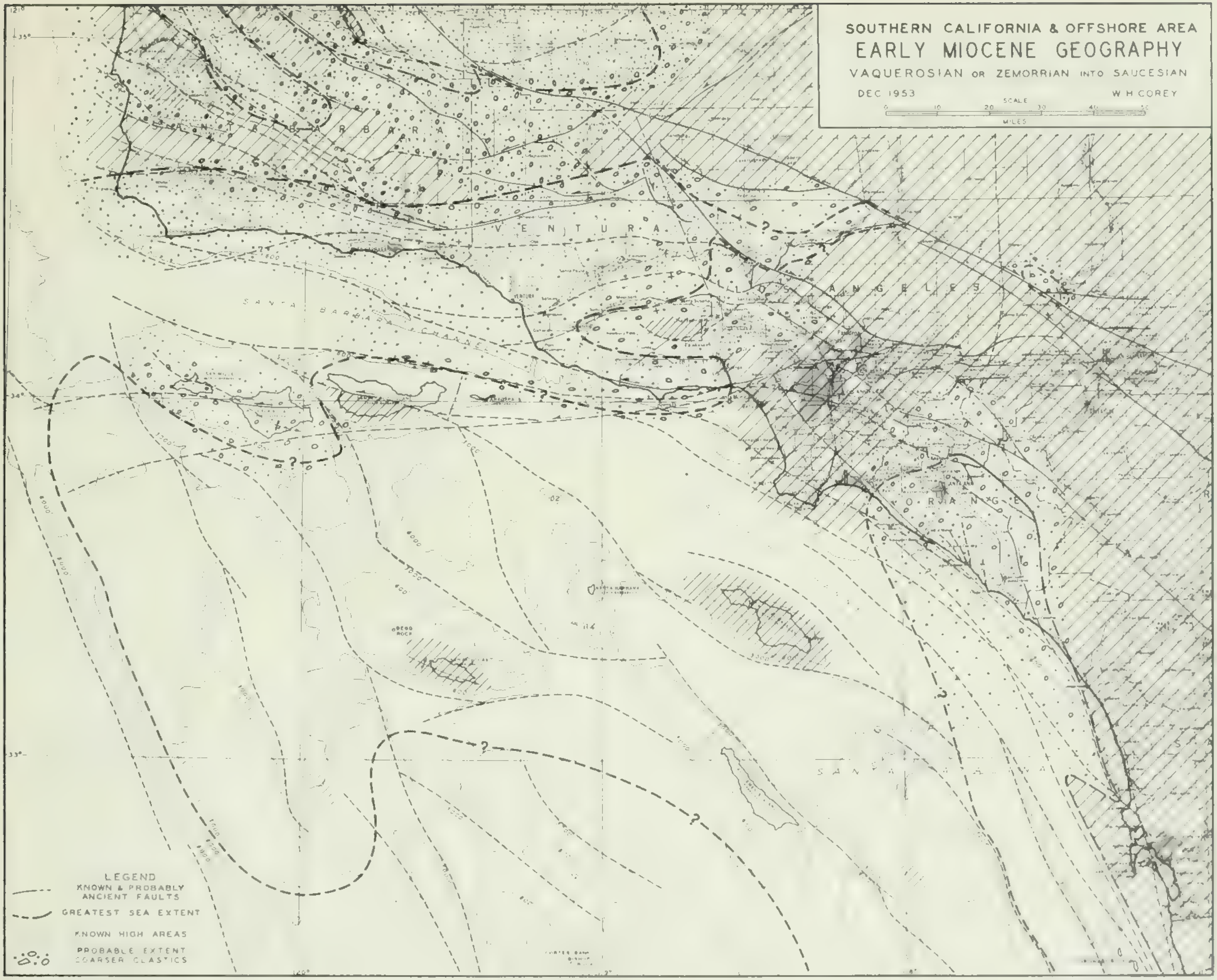

FIGURE 4. Map of a part of southern California, showing general geography and pattern of sedimentation in early Miocene time.

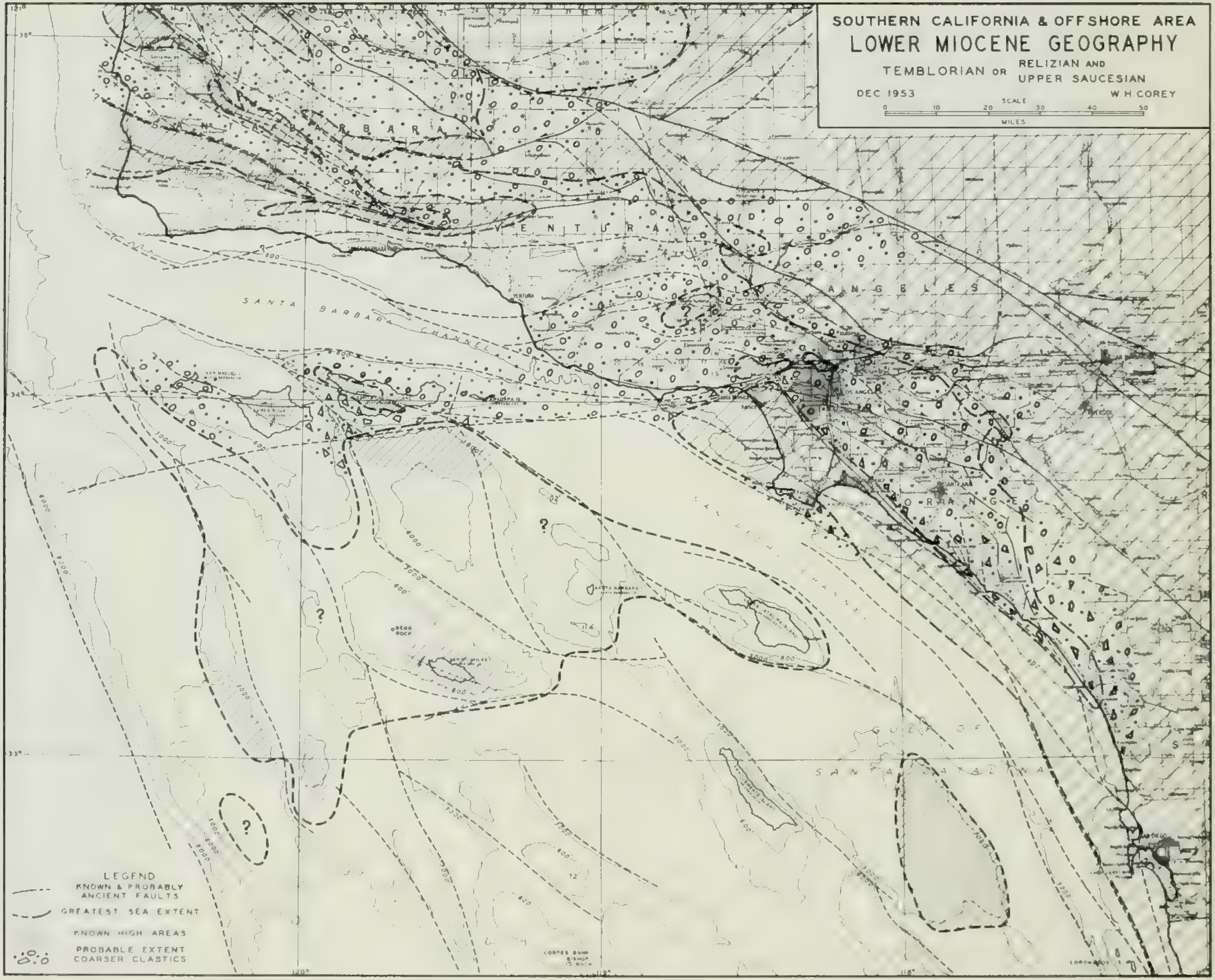

FIGURE 5. Map of a part of southern California, showing general geography and pattern of sedimentation in later early Miocene time.

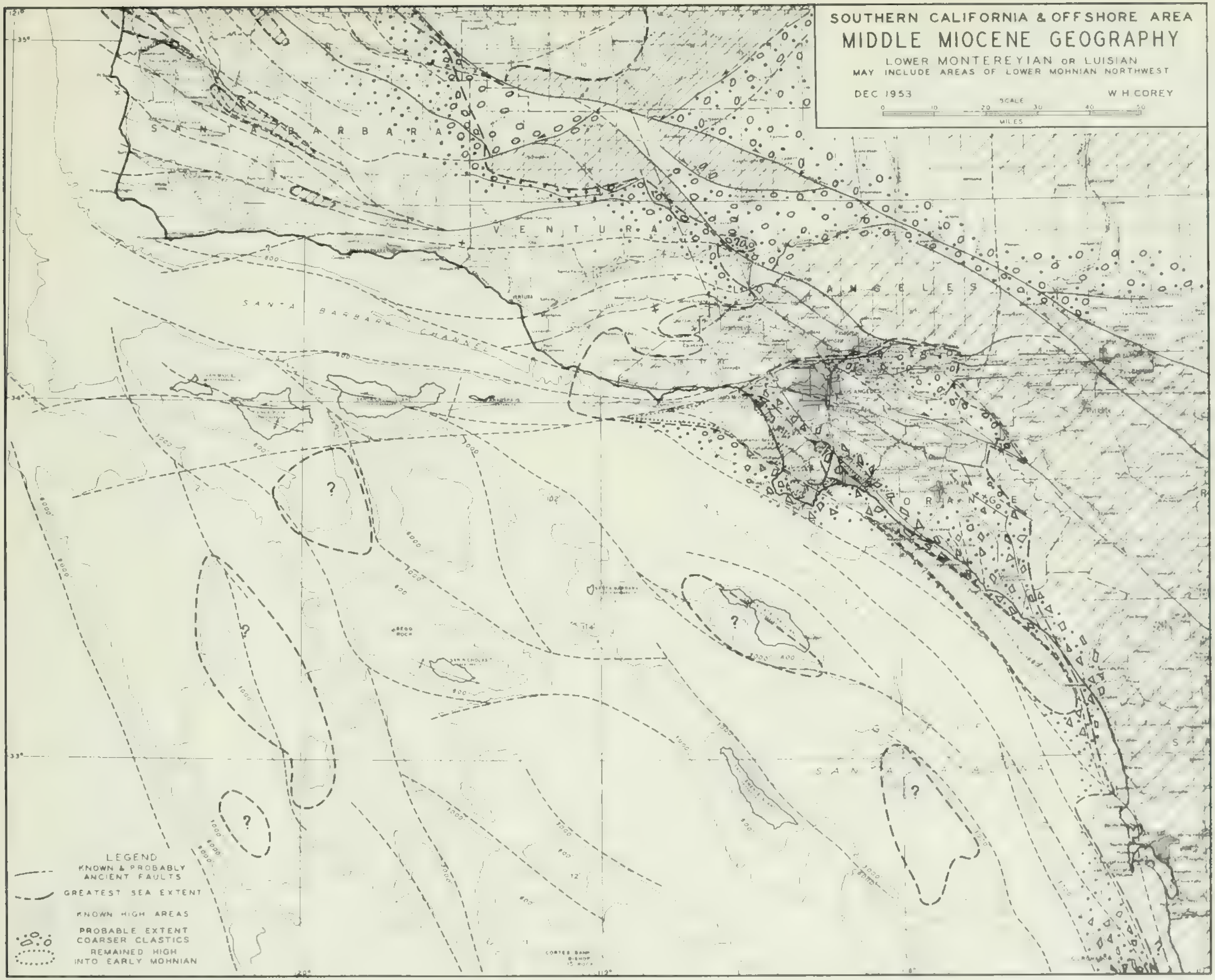
SOUTHERN CALIFORNIA & OFFSHORE AREA
MIDDLE MIOCENE GEOGRAPHY
LOWER MONTEREYIAN OR LUISIAN
MAY INCLUDE AREAS OF LOWER MOHNIAN NORTHWEST
DEC 1953
W H COREY
SCALE
MILES
SANTA BARBARA
VENTURA
LOS ANGELES
ORANGE
SANTA BARBARA CHANNEL
SAN DIEGO
?
LEGEND
KNOWN & PROBABLY ANCIENT FAULTS
GREATEST SEA EXTENT
KNOWN HIGH AREAS
PROBABLE EXTENT COARSER CLASTICS
REMAINED HIGH INTO EARLY MOHNIAN

FIGURE 6. Map of a part of southern California showing general geography and pattern of sedimentation in middle Miocene time.

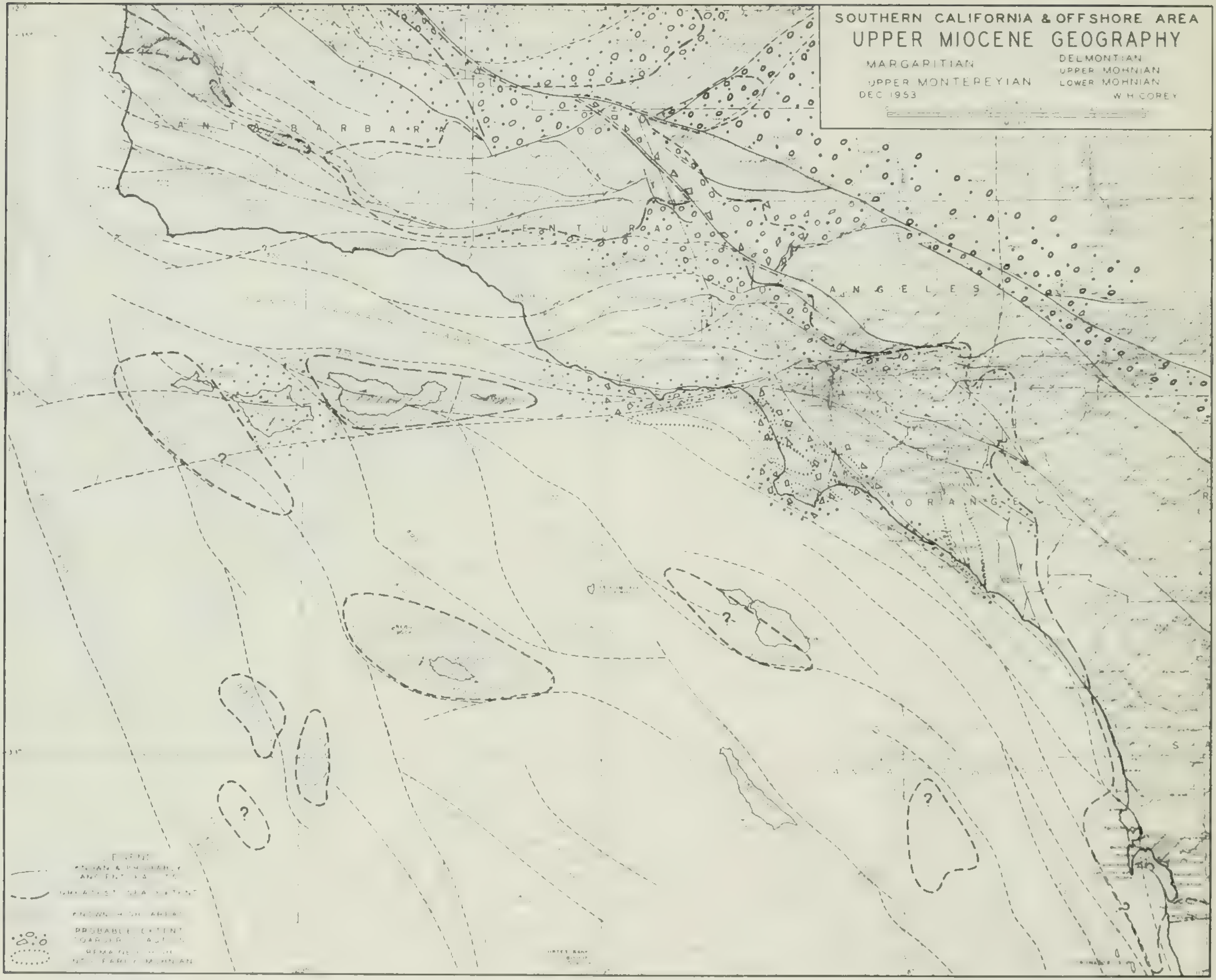

FIGURE 7. Map of a part of southern California, showing general geography and pattern of sedimentation in late Miocene time.

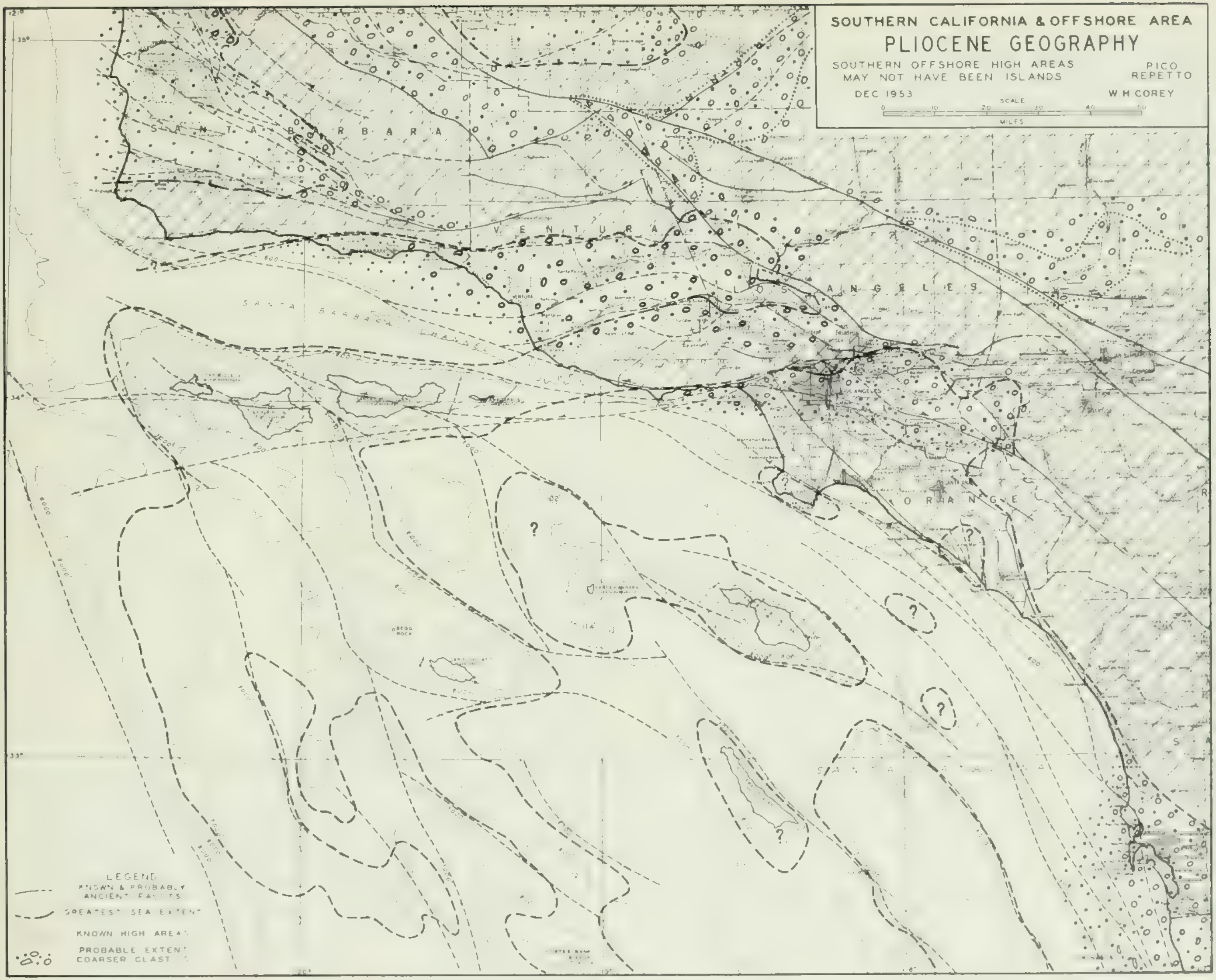

FIGURE 8. Map of a part of southern California, showing general geography and pattern of sedimentation in Pliocene time.

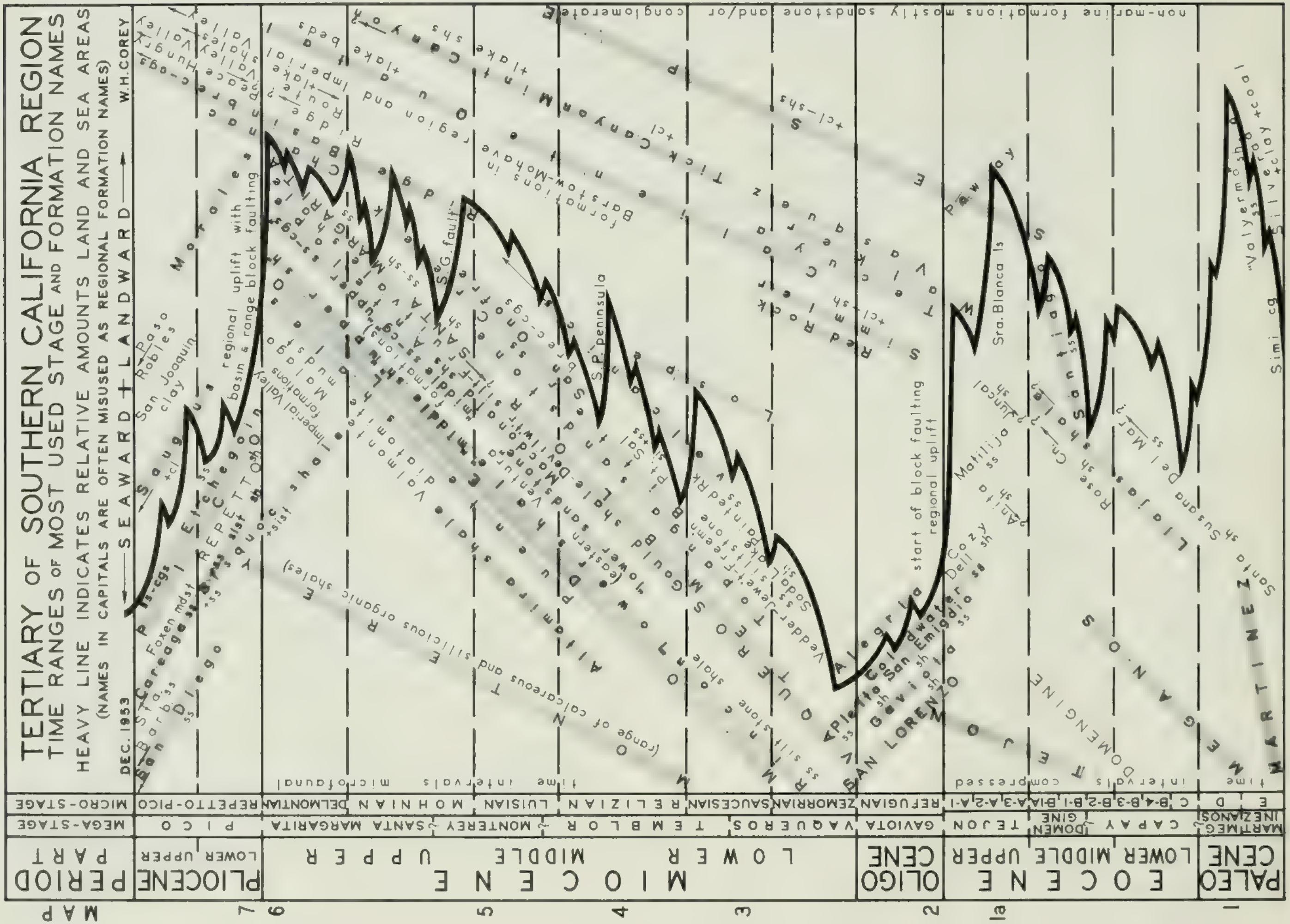

FIGURE 9. Correlation-transgression chart for Tertiary sedimentary units in a part of the southern California region.

moved over a terrain made increasingly irregular by development of a complex fault-block pattern of basins and ranges. Reversals of vertical relations between blocks, as well as great lateral offsets along some faults, occurred over the region through Miocene and Pliocene time. Many islands or highland masses, as well as deep embayments and basins, were formed at different times, only to founder or be broken up. The depositional areas and types of deposits in them varied considerably from place to place and from time to time. A new shifting of the blocks ended the Miocene epoch, and in Pliocene time some old basins were deepened, while elsewhere new basins and highland areas were formed.

Marine sediments of the entire region, as a result of this changing geography of post-Eocene time, were almost wholly clastic in nature, and were derived from land areas of varied rock types. The sediments in many areas comprised facies that became increasingly varied and restricted, although thick deposits of organic nature were laid down over large areas during episodes of greatest submergence in middle and late Miocene time. Much nonmarine deposition went on in coastal areas, as well as in many interior valleys, through all of Tertiary time except in the lower Pliocene.

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GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER IV

STRUCTURAL FEATURES

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Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER IV

STRUCTURAL FEATURES

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Editorial Note:

CHAPTER FOUR presents description and discussion of some of the major structural features in southern California, including several that appear to be highly unusual. The older elements of structure in this region are preserved in igneous and metamorphic rocks of pre-Cambrian, Paleozoic, and Mesozoic age, and reflect a complicated sequence of geologic events that is yet to be deciphered in most areas. Among the problems that have been attacked through a study of the older structural features in these rocks are the patterns of ancient highlands and basins of deposition, the nature and timing of metamorphism, and the sequence and mode of emplacement of the plutonic intrusives.

The younger elements of structure have received much more detailed attention, not only because the Cenozoic history of the region is relatively well recorded in the geologic section, but also because they constitute such an important part of this record. Dominant among these elements are master faults and fault zones that divide much of the region into gigantic blocks ranging from tens to thousands of square miles in exposed area. Many of these blocks are complicated internally by folds and additional faults. Some have had histories quite unlike those of adjacent blocks, and movements within and between blocks have taken place at different times in different areas. Deformation in many areas plainly is going on at the present time.

Numerous contributions in other chapters of this volume demonstrate the fundamental influence of diastrophism on the geologic history of southern California, and the dominance of faulting in the pattern and sequence of the tectonic events is emphasized by the contributions in this chapter. The major faults include low-angle thrusts, some of which appear to have been folded, and nearly vertical faults along which there has been considerable strike-slip movement. A remarkable feature is the absence of major normal faults from large parts of the region.

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1. TECTONICS OF FAULTING IN SOUTHERN CALIFORNIA*

BY MASON L. HILL †

INTRODUCTION

Our knowledge of southern California's structural plan is far from complete. However, the results of much good mapping at a scale of approximately half a mile to the inch are available for study on a regional basis. This work, stimulated principally by the search for oil, has been concentrated in terranes of Tertiary marine strata. Other mapping, in areas of metamorphic, plutonic, and volcanic rocks, areas of pre-Tertiary strata, and areas of Tertiary and Quaternary continental beds, has been accomplished mainly by State and Federal agencies and by members of academic institutions.

Much of the mapping, although done for various purposes, portrays significant surface structural data. Numerous holes drilled in the search for oil, perhaps with a density of spacing greater than elsewhere in the world, add much subsurface structural information down to depths of 2 miles, again in the areas of marine Tertiary strata. Reflection seismograph coverage, obtained primarily in the search for oil within the Tertiary marine basins, has furnished some important structural data, also to depths of approximately 2 miles. Recent oceanographic studies by various agencies, institutions, and oil companies have brought to light data of structural significance off the coast of southern California. And finally, seismic studies in this region of frequent earthquakes, principally by seismological institutions and Federal agencies, have revealed important structural information, particularly because such studies give data from depths of tens to hundreds of miles beneath both land and sea.

The sum of information from these and other sources is truly impressive, and although more and better data undoubtedly will come to hand from future investigations, it becomes periodically feasible, and scientifically advisable, to make tentative interpretations. The purpose of this paper is to utilize the currently available data in attempting answers to the following questions: What are the significant elements of structure in the southern California region? What are the apparent dynamics of these features? What can be deduced about their geologic history and origins?

In this day of ever-increasing production and specialization, one geologist obviously cannot see all, read all, and understand all the tectonic aspects of southern California. The present restricted approach is one of describing structural samples of the region, chosen for their apparent bearing on the questions stated above.‡ The samples are faults because many long and deep ones are well distributed over the entire region, and because the dynamics of faulting probably is better understood than any other type of crustal deformation (see Anderson, 1942). The prime information relative to the dynamics of faulting is the determination of sense of movements on the faults. The true net slip or shift on a fault usually is difficult to determine, as special conditions and criteria are required. Too often separation (offset) is taken to represent actual relative movement.

The next information essential to the understanding of the dynamics of faulting is the relationship of the faults to one another. Involved here are pattern (both strike and dip relationships), relative size, relative age, and history. In other words, a fault dynamical system comprises integrated movements on faults in response to a single deformational environment (the strain effect from the causal stress). It is of course essential to know that the faults are related in space and time as manifestations of a single strain system. Difficulties are introduced by uncertain age determinations of the faults, as dynamical analyses of the movements must be based on the assumption that a single strain system is involved rather than two or more (lesser or greater; older or younger) separate deformations.

The reasoning employed here is founded on the premise that an understanding of the dynamics of faulting will be an index to the primary pattern of deformation in southern California. It is believed that the senses of the movements on many of the major faults in this region are now well enough known so that an approach to the problem can be made at this time. It also is believed that with this knowledge it should be possible to incorporate other structural features, such as folds and minor faults, into the primary pattern of deformation. Furthermore, it is believed that from these analyses it will be possible to make some sound inferences regarding the orientation of stresses that are responsible for the regional strain pattern; these in turn should provide some understanding of the origin of crustal deformations.

GEOLOGIC SETTING

Southern California is a region of sharp geomorphic and geologic contrasts resulting from the juxtaposition of blocks, commonly separated by faults, that are made up of dissimilar rock types, sedimentary sections, and structures, and that have unlike geologic histories. The correlation of geomorphology and geology permits subdivision of the region into several provinces. This has been done in various ways, and in more or less detail, but most of the divisions

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* Published by permission of the Richfield Oil Corporation.

† Chief Geologist, Richfield Oil Corporation, Los Angeles. The author is indebted to many co-workers for data and ideas relative to California tectonics, and to Marie Clark, Rollin Eckis, and A. O. Woodford for criticism of the manuscript.

‡ The reader is referred to other papers and maps in this volume and to the Geologic Map of California (Jenkins, 1938) for systematic regional geology.

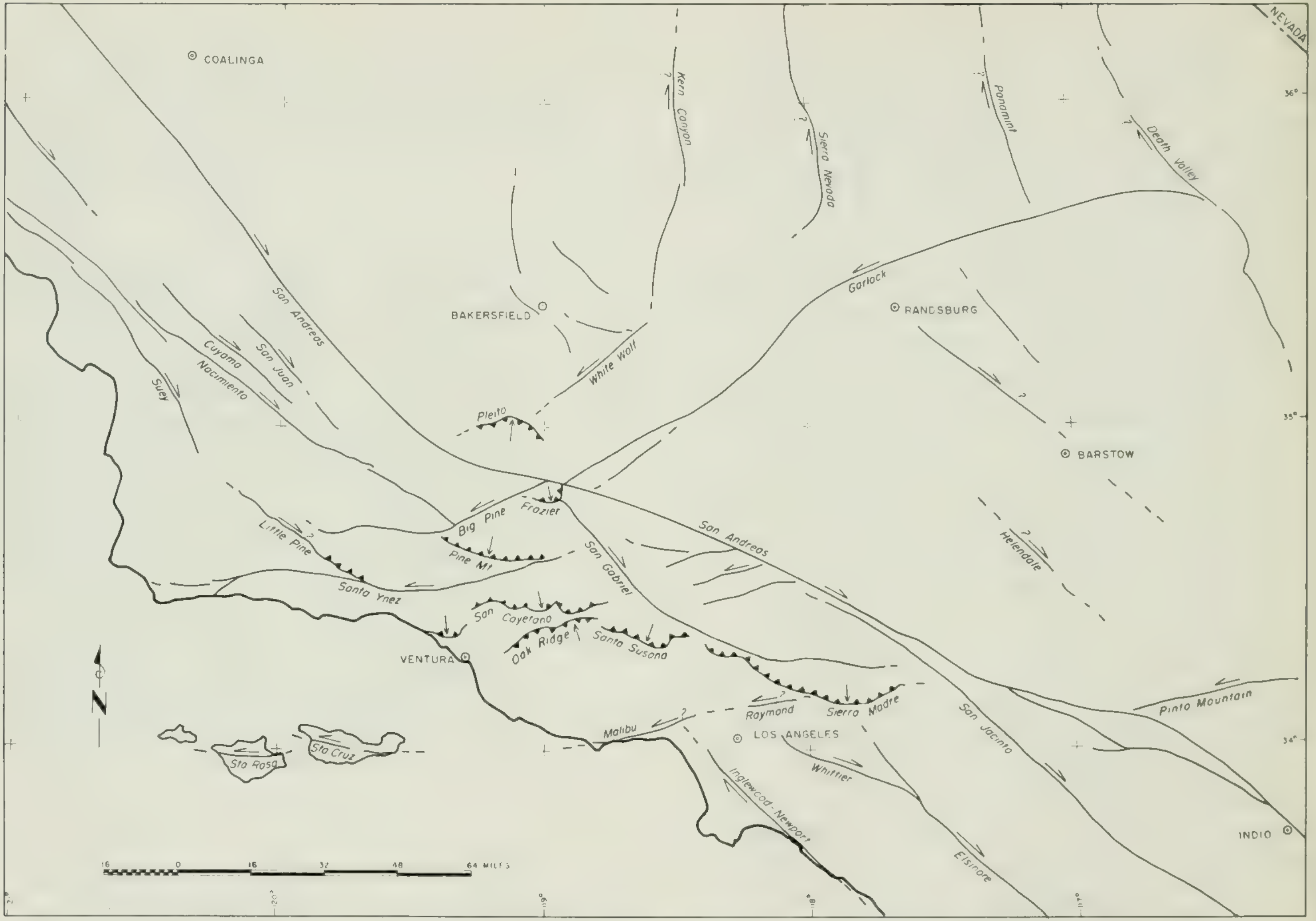

FIGURE 1. Map showing major faults in southern California. Arrows suggest principal component of relative movement.

cannot be regarded as wholly fundamental in a geologic sense. Thus, when individual ranges and valleys are separated, the basic geologic attributes of larger units are likely to be violated, and when large regions are defined according to the distribution of major rock types (e.g., "basement" rocks, Reed and Hollister, 1936), certain significant geomorphic attributes are consequently ignored.

A useful geomorphic-geologic subdivision of southern California has been made as follows (see Geomorphic Map of California, Jenkins, 1938): (1) Southern Coast Ranges, including the Salinas and Cuyama marine Tertiary basins; (2) Southern San Joaquin Valley marine Tertiary basin; (3) Southern Sierra Nevada-Tehachapi Mountains and the southwestern part of the Basin-Ranges province, including Owens, Panamint, and Death Valleys; (4) Mojave Desert block, the westward pointing wedge that lies south of the Basin-Ranges province; (5) Transverse Ranges, trending anomalously eastward and marking the southern ends of the provinces noted above. The western part of this unit includes the Santa Maria and Ventura marine basins; (6) The Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa) and adjacent submerged area, between the east-trending coast line and the continental slope. This province is geologically qualified as a part of the Transverse Ranges; (7) Los Angeles marine Tertiary basin; (8) Offshore area west and southwest of the Los Angeles basin, including Catalina and San Clemente Islands; (9) Peninsular Ranges, extending from the Transverse Ranges south-southeastward into Baja California, and forming the east border of the Los Angeles basin; (10) Colorado Desert block of southeastern California, which lies south of the Transverse Ranges and east of the Peninsular Ranges, and which includes the continental Tertiary basin of the Coachella-Imperial Valley.

The principal rock units in southern California, viewed in terms of tectonic behavior, are: (1) Unmetamorphosed marine Paleozoic sediments of the Cordilleran geosyncline in the southwestern Basin-Ranges province; (2) Pre-Cretaceous metamorphosed sedimentary rocks and associated granitic rocks of the northeastern Salinas basin, the Sierra Nevada and Tehachapi Mountains, the eastern Transverse Ranges, the Mojave and Colorado Desert blocks, and the Peninsular Ranges; (3) The Franciscan group and other Mesozoic marine sediments and basic intrusives of the southern Coast Ranges, the western part of the Transverse Ranges, the southwestern corner of the Los Angeles basin, and Catalina Island; (4) Thick sections of Cretaceous strata, mainly marine shales and sandstones of the southern Coast Ranges, the western part of the Transverse Ranges, and the east margin of the Los Angeles basin; (5) Very thick sections of largely marine Tertiary strata in the southern Coast Ranges, the San Joaquin basin, the western Transverse Ranges, the Channel Islands, and in the Ventura and Los Angeles basins. Thinner continental Tertiary deposits are present in the Basin-Ranges, Mojave Desert, and Colorado Desert provinces.

Strain response to causal stress is significantly influenced by the characteristics of the rocks involved. Thick sedimentary sections commonly deform by folding, with relatively close folds and reverse or thrust faults common in the regional uplifts, and broad and gentle folding common in the relatively depressed areas. Granitic terranes, and thin sedimentary sections overlying such rocks, generally deform by faulting. Franciscan rocks vary in their tectonic responses because some of the sandstones, metamorphosed or highly lithified sediments, and igneous rocks are relatively competent, whereas some of the shales, cherts, and serpentines are incompetent.

Rock competency thus influences the relative importance of faulting and folding within southern California, as one might expect from dynamical theory and world-wide experience. Further, such control of structural type is particularly impressive in this region of thick and semi-isolated basins of Tertiary marine strata. However, an important exception to this rule of deformation also is particularly impressive in California. It is evidenced by the common occurrence of lateral faults (Hill, 1947), many of which extend through more than one geomorphic-geologic province without regard to rock type, stratigraphic thickness, or competency. These lateral faults seem to occur just as commonly in areas with thick sections of incompetent sediments as in areas of granitic rocks. It is reasoned, therefore, that these faults have been propagated upward through rocks of all types from more homogeneous material at depth (near the usual 10-mile depth of earthquake foci), whereas many of the outcropping thrust faults probably originate within the relatively incompetent material of their surface occurrence.

The principal structural features of southern California occur in the geomorphic-geologic provinces as follows: (1) Many northwest-trending folds and faults are present in the southern Coast Ranges. The larger faults characteristically trend more northerly than the folds and associated smaller faults. (2) The southern San Joaquin Valley is an asymmetric basin in which the contained strata mostly dip and thicken southwestward. It is characterized by gentle and variously oriented folds, and locally takes on the structural aspects of the Coast Ranges to the west, the Transverse Ranges to the south, and the Sierra Nevada-Tehachapi Mountains to the east. (3) The southwestern Basin-Ranges province, including the Sierra Nevada, is structurally characterized by northward-trending horst and graben blocks. The mountain blocks show complicated older structural features. (4) The Mojave Desert block is characterized by northwest-trending faults, and by northwest-trending folds where the continental Tertiary strata are thickest. (5) The Transverse Ranges, including the Channel Islands, are typified by eastward-trending folds and fault blocks. (6) The Los Angeles basin is characterized by west-northwestward-trending folds and northwestward-trending faults, and similar features occur in the adjacent offshore region. (7) The Peninsular Ranges are typified by northwestward-trending fault blocks. (8) The Colorado Desert is characterized by fault blocks of diverse trends, and by sharp, west-northwestward-trending folds and northwest-trending faults in areas of thick continental Tertiary beds.

TECTONIC PATTERN

The primary structural elements of southern California are two sets of major faults (fig. 1). These faults range in length from tens to hundreds of miles, and some of them are known, from seismic evidence, to extend to depths of at least 10 miles. They are characterized by lateral slips. The most prominent set trends northwest and shows right lateral movement (San Andreas, and others), whereas the other set trends east-northeast and shows left lateral movement (Garlock, and others). Such faults are considered to be primary structural features of the region because they are longer and probably deeper than the other prominent features (reverse faults, thrust faults, and folds), which are restricted to separate geomorphic-geologic provinces. Thus an understanding of the dynamics of this primary fault pattern should provide the correct approach to the understanding of the development of more local, and perhaps even more regional, structure.

The movements on these two sets of faults establish a regional strain pattern of relatively outward moving wedges in an east-west direction and a relative shortening in a north-south direction. This systematic strain pattern appears to extend over an area of more than 100,000 square miles, as determined by the products of the lengths of the conjugate San Andreas and Big Pine-Garlock faults, and appears to have been in existence for more than 100 million years, as evidenced by the probable age of the San Andreas fault. This strain pattern is considered to be geotectonically important because it represents both a significant size, with respect to the earth's surface, and a significant period of time, with respect to the earth's history. Furthermore, the amount of deformation, as indicated by possible cumulative offsets on some of the lateral-slip faults amounting to tens or even hundreds of miles, appears to be of major significance.

This primary strain pattern is offered as a working hypothesis that obviously requires further checking. Of paramount importance is the orientation of the principal component of displacement on each of the major faults. It is believed that reliable data are available for enough of the major faults to firmly establish relative east-west extension and north-south shortening as the primary strain pattern.

The next important check of the hypothesis is an analysis of local strain patterns, which should be reconcilable with the primary pattern. It is believed that the east-west trending folds and thrust faults of the Transverse Ranges do fit the pattern as indicating a secondary, upward relief to the regional north-south shortening (fig. 2). It also is reasonable to expect that in the southern Coast Ranges the northwest trending folds and thrust faults should develop as secondary northeast-southwest shortening and upward relief in this region of numerous major right lateral-slip faults that trend more northerly.

The final check, and of utmost importance relative to theories of geotectonics, is the harmonizing of the primary strain pattern in southern California with those of adjacent large regions, as the eastern Pacific border and the Rocky Mountains. The orientation and origin of the stresses responsible for the primary strain pattern of this region are as yet unknown, although possible answers to these problems are discussed farther on.

MAJOR RIGHT LATERAL FAULTS

A few examples of important northwest-trending, right lateral-slip faults are described below. According to the present thesis, these faults constitute one set of a conjugate fault system that forms the primary strain pattern of southern California. Of these right lateral-slip faults the San Andreas is discussed first, because it is the greatest as indicated by length (600+ miles), displacement (perhaps measured in hundreds of miles), and age (perhaps active since Jurassic time), and because as the major structural feature of California, it is tectonically the most significant.

San Andreas Fault. The San Andreas fault (Hill and Dibblee, 1953) extends from at least as far south as the Gulf of California northwestward through the Colorado Desert, Transverse Ranges, and Coast Ranges (type locality is at Lake San Andreas on the San Francisco Peninsula), and thence offshore an unknown distance northwestward from Point Arena. Prominent along its Recent trace are sag ponds, ridges, truncated spurs, offset drainage lines, and scarps (see Noble, Contribution No. 5, this chapter). The fault zone comprises many local, sub-parallel, steep faults, not all recently active, and is as much as several miles wide in some areas. Dissimilar rock types and sequences are characteristically in contact along this zone. The throw is reversed many times along the trace of the San Andreas fault zone, and these reversals of apparent vertical movement are considered to be due in part to the juxtaposing of unlike topographic elevations and rock sequences by lateral movement.

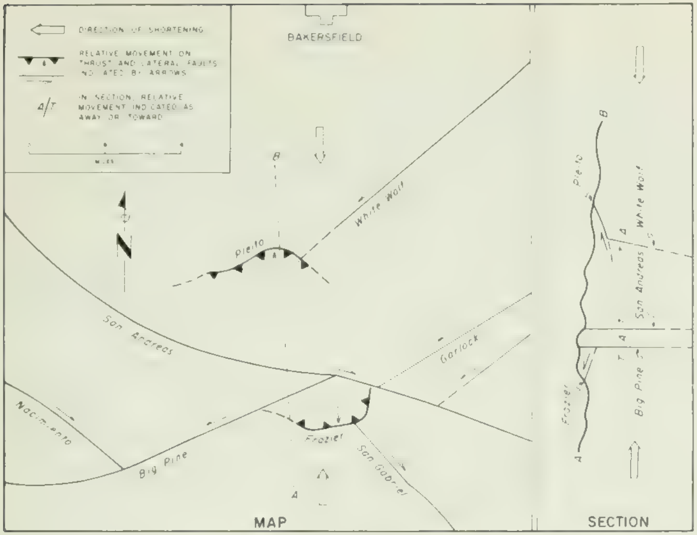

Figure 2. Map and section showing strain pattern in a part of southern California. The pattern includes primary east-west relative extension on lateral faults, and secondary upward relief on thrust faults.

The San Andreas fault is characterized by right lateral movement. Except in some masses of Recent alluvium, these movements have occurred almost everywhere along its course. Right lateral displacements of 21 feet and 10 feet occurred on the fault during the 1906 San Francisco earthquake and the 1940 Imperial Valley earthquake, respectively. Present drainage lines are clearly offset in many places along the fault, and indicate right lateral displacements of as much as one mile. Some older stream channels and terrace deposits of Recent and Pleistocene age on the north side of the San Gabriel Mountains appear to be offset several miles (Wallace, 1949; Noble, Contribution No. 5, this chapter). Pleistocene strata are offset approximately 14 miles in a right lateral sense by the fault in the southern Temblor Range, and an upper Miocene facies contact appears to be offset about 65 miles in the same region. Miocene and Eocene strata appear to be displaced at least 20 miles, and perhaps much farther, in the San Gabriel and San Bernardino Mountains.

The petrologic similarity of the northwest end of the body of Pelona schist in the San Gabriel Mountains and the northwest end of the body of Orocopia schist near the Salton Sea, on the other side of the San Andreas fault, suggests the possibility of an accumulative right lateral-slip of approximately 160 miles in this southern area. Similar interpretations of regional geology indicate or suggest that movements of the same sort in the Coast Ranges have amounted to 175 miles since early Miocene time, 225 miles since Eocene time, 320 miles since Cretaceous time, and perhaps to more than 350 miles since Jurassic time. Figure 3 shows these accumulative, and possibly progressive, offsets on the San Andreas fault since Jurassic time, and the insert palinspastic maps (Kay, 1945) suggest possible space relationships at two stages in the history of this fault zone.

San Gabriel Fault. The San Gabriel fault (Crowell, 1952) extends from the San Andreas fault in the San Emigdio Mountains southeastward and eastward into the San Gabriel Mountains. It is steep and straight, and marks a contact between dissimilar rock types. Its throw reverses along the trace. It separates the Ventura basin from the Soledad and Ridge basins, as indicated by their unlike sedimentary types, sequences, and faunal facies (Bailey and Jahns, Contribution No. 6, Chapter II). Upper Miocene conglomerate, composed largely of anorthosite clasts, occurs immediately southwest of the fault in the eastern Ventura basin, and evidently was derived from a unique in situ occurrence of anorthosite in the western San Gabriel Mountains (Crowell, Contribution No. 6, this chapter). The space relationship between source and depositional sites thus indicates approximately 20 miles of right lateral-slip on the San Gabriel fault since upper Miocene time.

Other Right Lateral-Slip Faults. In the southern Coast Ranges are several northwest-trending faults on which cumulative right lateral-slips probably amount to as much as several miles. In sequence southwest of the San Andreas fault they include the San Juan, Cuyama, Nacimiento, and Suey faults (fig. 1). These faults have apparent reversals of throw along their trend, and they separate unlike rocks and rock sequences. They are long, steep, and probably deep faults that trend approximately parallel to the San Andreas, and hence are at least suspect of having important right lateral displacements. The San Juan fault, for example, appears to displace a depositional contact of lower Miocene strata on granitic rocks near La Panza, T. 30 S., R. 17 E., MD., at least 12 miles in a right lateral sense (see Geologic Map of California, Jenkins, 1938). The Nacimiento fault zone separates granitic and Franciscan basement rocks for a distance of nearly 200 miles to indicate the possibility of great strike-slip displacement. The Russell Ranch fault, possibly the buried southeastern extension of the San Juan fault, is known by stratigraphic relationships and electric-log correlations to show a 5-mile right lateral offset of lower Miocene strata.

In the Basin-Ranges region of southern California are several important north-northwest-trending faults that may have substantial right lateral components of displacement, although normal-slip faulting generally has been implied. These include the Sierra Nevada fault, on which, at the time of the Owens Valley earthquake of 1872, the maximum surface displacement comprised 23 feet of dip-slip and 20 feet of right lateral-slip (California Division of Mines, 1952), and faults in the Panamint Valley and Death Valley areas.

In the Mojave Desert province at least some of the northwestward-trending faults appear to have right lateral-slip components of displacements (T. W. Dibblee, Jr., and D. F. Hewett, personal communications). Several of these faults extend southeastward into the Transverse Ranges, and probably are tectonically analogous to the above described northwest-trending segment of the San Gabriel fault.

In the Los Angeles basin the important northwestward-trending Inglewood-Newport fault zone possibly separates unlike Miocene strata and unlike basement facies (Schoellhamer and Woodford, 1951; Woodford, et al., Contribution No. 5, Chapter II). It is overlain by east-southeastward-trending en-echelon folds, and electric-log correlations demonstrate a few miles of right lateral-slip. The Whittier fault also has a component of right lateral-slip, as shown by offset drainage lines (e.g., Brea Canyon) and perhaps by a 3-mile offset of a lower Miocene formation (A. O. Woodford, personal communication).

In the eastern San Gabriel Mountains the northwest-trending San Jacinto fault appears to be characterized by right lateral movement (Arnett, 1949). In the Peninsular Ranges the parallel San Jacinto and Elsinore faults may have right lateral displacements (Dibblee, Contribution No. 2, and Jahns, Contribution No. 3, Chapter II). Both of these faults are characterized by long, straight, steep, wide, and probably deep (10-mile earthquake foci) zones that have topographic and apparent geologic reversals of throw along their traces.

MAJOR LEFT LATERAL FAULTS

Garlock Fault. The Garlock fault (Hulin, 1925; Hill and Dibblee, 1953; Dibblee, 1953) extends east-northeastward from the San Andreas fault for a distance of 150 miles. It sharply separates the Basin-Ranges and Mojave Desert provinces, and thus is an important contact between unlike geomorphic units, rock units and sequences, and structural features. The trace of this fault, which is clearly revealed, is straight and steep, and the fault probably extends to depths of at least 10 miles. Reversals of topographic and geologic throw are common along the zone. Recent displacements are left lateral, as indicated by drainage offsets of half a mile and, near the type locality at Garlock Station, by tension trenches. A contact between Paleozoic strata and granitic rocks appears to have been offset by the Garlock fault a distance of about 6 miles.

Big Pine Fault. The Big Pine fault (Hill and Dibblee, 1953), located in the Transverse Ranges, extends 50 miles west-southwestward from the San Andreas fault. It is relatively straight and steep, and probably is deep. Apparent reversals of throw occur along it. Drainage offsets are left lateral, and the distribution of rock units, rock sequences, and structural features indicates a left lateral displacement of as much as 14 miles. This fault zone is of particular interest because of the possibility that it is an offset part of the Garlock fault west of the San Andreas, and because it strengthens the concept of conjugate strike-slip faults in southern California.

Other Left Lateral-Slip Faults. East-northeastward-trending faults that may have left lateral-slip components of displacement include the White Wolf, the Santa Ynez (Dibblee, 1952), several faults in the western San Gabriel Mountains (Jahns, 1940), the Malibu Beach-Raymond fault zone, the Pine Mountain fault, and the Santa Cruz Island and Santa Rosa Island faults (fig. 1). The Santa Rosa Island fault shows especially convincing left-lateral offsets of drainage lines, as well as a possible 4-mile offset of lower Miocene beds (Anderson, Redwine, and McGovney, 1949; J. R. Pemberton, personal communication).

REVERSE AND THRUST FAULTS

In the Transverse Ranges are several prominent reverse and thrust faults, including the Pleito and Frazier, which are of special tectonic interest in association with the Big Pine-Garlock and San Andreas zones (fig. 2), and the Pine Mountain, San Cayetano, Oakridge, Santa Susana, and Sierra Madre faults. Such faults are less common in the other provinces, and even in the Transverse Ranges they are considered to be secondary to the lateral-slip faults described above.

Noteworthy is the absence of major normal-slip faults from most parts of southern California, although several of those in the Basin-Ranges province may be important exceptions.

PROBLEMS OF FAULTING

General Features. Where are the important faults in southern California? This fundamental question has not yet been satisfactorily answered. Actually the most recently published fault maps, the Tectonic Map of the United States (Longwell, et al., 1944) and the Geomorphic Map of California (Jenkins, 1938), are astonishingly like the earliest fault map of the State (Lawson, 1908).

What is the sense of relative movement on each major fault? These determinations are of utmost importance to the understanding of the mechanics of regional deformation, but they have been assumed (usually from cross-section offsets) more often than determined. The approximate orientation of relative movement on faults generally can be determined from collection and three-dimensional analysis of pertinent fault-zone and fault-block data.

What are the duration and cumulative amount of movements on each major fault? These determinations are essential to the understanding of regional tectonic history. Approximate answers to such problems also are possible with collection and analyses of pertinent stratigraphic and petrologic data. Evidence of lateral displacements can be obtained by matching basement rock facies, sedimentary facies, stratigraphic thicknesses and sequences, unconformities, faunal facies, deposits from specific source areas, and structures on opposite sides of the faults. The matching of basement rock facies will require much additional mapping and petrographic work, and will be the most significant approach to the determination of total cumulative movements on the faults.

Although the major strain system of north-south shortening involves right lateral movements on the northwest-trending faults, there appear to be a few contradictions that need explanation. These include a fault in the southern Coast Ranges (L. E. Redwine and R. G. Maynard, personal communication), a fault in the Mojave Desert (T. H. McCulloh, personal communication), and a fault in the Sierra Nevada (Durrell, 1950).

San Andreas Fault. What is the San Andreas fault? Is it only manifest by its nearly continuous 600+ mile Recent trace, or is it a zone in which segments include several important mapped fault strands? Where and how far does it extend beneath the sea, both to the northwest and to the southeast? At what dip(s) and to what depths does the San Andreas extend? When was its inception? Does it date from the Pleistocene, or from at least as far back in time as the Jurassic? What has been the nature of movements on this fault? Have right lateral-slips been the principal movements, or were dip-slip displacements important at earlier stages in its history? Has the net cumulative amount of lateral displacement been several thousand feet, or as much as several hundred miles?

Inasmuch as the San Andreas is the major fault in California, and one of the larger mapped faults of the world, it is surely desirable to solve the problems concerning it. But few, or perhaps none, of the above questions are satisfactorily answered, although it is possible, and even likely, that most of these problems will be attacked and ultimately settled because the history of this fault is so obviously an important key to geotectonic history.

The alternative questions in the list above perhaps adequately express the current principal differences of opinion regarding the San Andreas fault, and it is only fair to state that the present writer differs from many other investigators in his interpretation of these particular problems. The writer is inclined to believe that the San Andreas is a zone along which some segments are several miles wide and contain several separate fault strands, that the fault zone was first developed in pre-Cretaceous time, that right lateral-slips have characterized the movements on it from its inception to the present time, and that the total right lateral displacement amounts to at least 65 miles and perhaps to more than 350 miles.

Earthquakes. Southern California lies in the circum-Pacific seismic belt, where concentrations of seismologists and seismological apparatus are strategically situated for the application of the principle of uniformitarianism to fundamental fault tectonic problems. Many data that bear on these problems have been obtained by seismic methods. Perhaps most important are the numerous locations of earthquake epicenters and calculations of focal depths. More recently determinations of the orientation of fault-slip by first motions, dilational or compressional, at seismograph stations and analyses of after-shock sequences are adding to knowledge of regional strain-stress relationships. Each study of a large earthquake is likely to bring out new data and principles of great tectonic significance. For example, the San Francisco earthquake of 1906 was responsible for the elastic rebound theory (Reid, 1908) and for systematic triangulation-net surveys (Whitten, 1948). The 1952 Arvin-Tehachapi earthquake is still furnishing data of seismic and tectonic significance.

One of the geologic problems associated with earthquakes is the assignment of responsibility to a known fault (Louderback, 1942). This has been done occasionally in California, where the sense of fault displacement has been shown by the sudden development of surface dislocations along a particular fault trace. Surface dislocations are seldom developed, however, and obviously are unlikely in view of the fact that the normal focal depth of both large and small earthquakes in this region is approximately 10 miles. In some instances, a surface dislocation is developed along a fault without an accompanying appreciable seismic disturbance (Koch, 1933). For example, late in 1949 a movement of a few inches occurred along the surface trace of a fault on the east side of the San Joaquin Valley 8 miles north of Bakersfield, and was observed by the writer with L. B. McMichael. This disturbed zone was followed over ridges and across small, westward-draining valleys for a distance of 2 miles. The seismological stations in Pasadena and Berkeley were advised of the approximate date of the movement, but no seismic activity was recorded for that area during that time (Beno Gutenberg and Perry Byerly, personal communications).

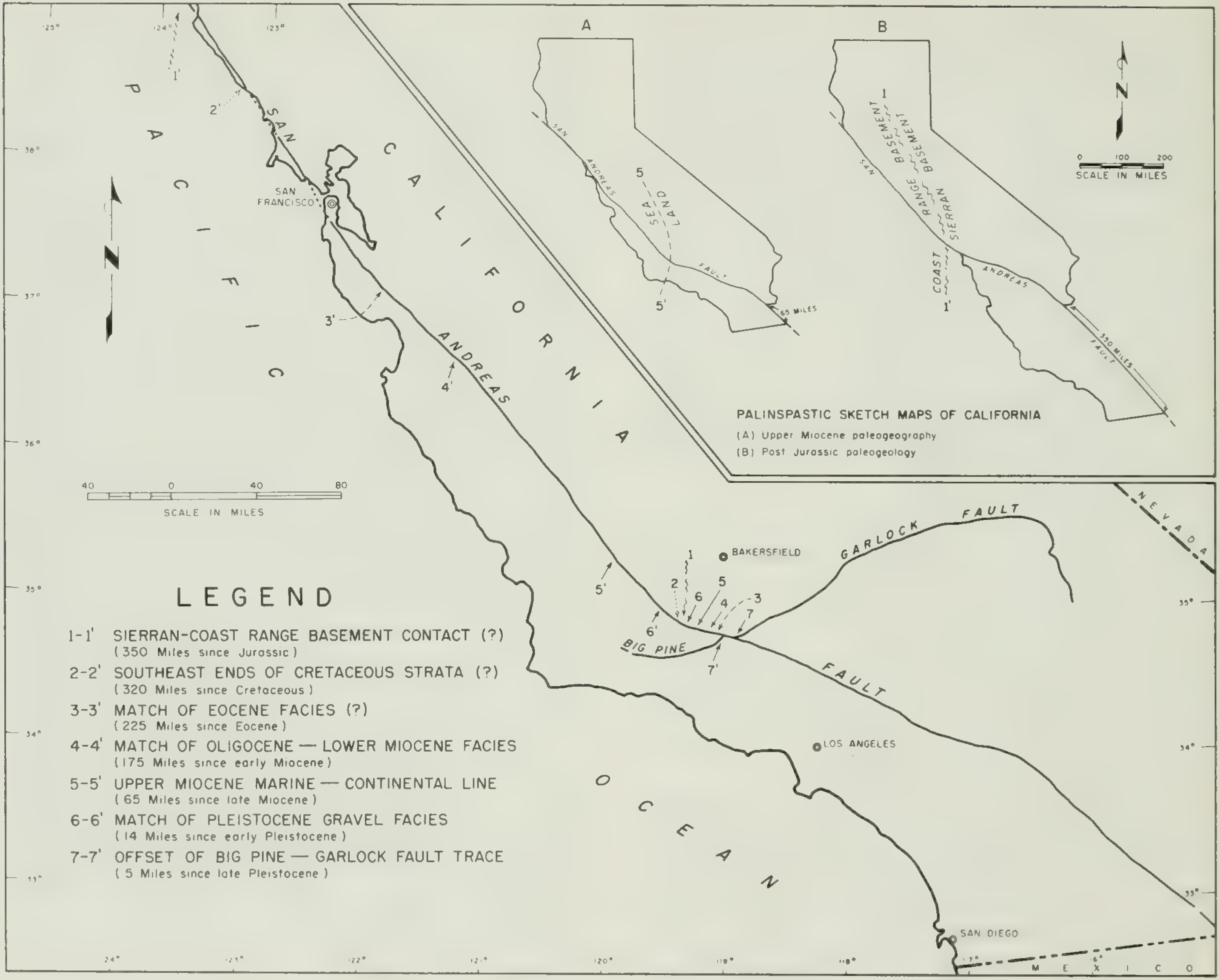
PACIFIC OCEAN
CALIFORNIA
SAN ANDREAS FAULT
SAN FRANCISCO
BAKERSFIELD
LOS ANGELES
SAN DIEGO
GARLOCK FAULT
BIG PINE
NEVADA
MEXICO
N
SCALE IN MILES
40 0 40 80
1'
2'
3'
4'
5'
6'
7'
1
2
3
4
5
6
7
A
B
SEA
LAND
65 MILES
350 MILES
SIERRAN
COAST RANGE BASEMENT
SCALE IN MILES
0 100 200
PALINSPASTIC SKETCH MAPS OF CALIFORNIA
(A) Upper Miocene paleogeography
(B) Post Jurassic paleogeology
LEGEND
1-1' SIERRAN-COAST RANGE BASEMENT CONTACT (?)
(350 Miles since Jurassic)
2-2' SOUTHEAST ENDS OF CRETACEOUS STRATA (?)
(320 Miles since Cretaceous)
3-3' MATCH OF EOCENE FACIES (?)
(225 Miles since Eocene)
4-4' MATCH OF OLIGOCENE — LOWER MIOCENE FACIES
(175 Miles since early Miocene)
5-5' UPPER MIOCENE MARINE — CONTINENTAL LINE
(65 Miles since late Miocene)
6-6' MATCH OF PLEISTOCENE GRAVEL FACIES
(14 Miles since early Pleistocene)
7-7' OFFSET OF BIG PINE — GARLOCK FAULT TRACE
(5 Miles since late Pleistocene)

FIGURE 3. Progressive offsets on the San Andreas fault, shown by 1-1' to 7-7'.

A most worthwhile avenue of geologic-geophysical research is the continuing attempt to solve the problem of earthquake prediction, although the human time scale is so disproportionate to the geologic scale that the solution of this problem for human application will be exceedingly difficult. Most faults in southern California must be considered active because they are planes of weakness in a region undergoing strain. New zones of faulting also may be affected by this strain. However, there are so many evenly distributed mapped faults in the region that it is anybody's guess as to which one (or possibly some unmapped or subsurface one) will be responsible for the next earthquake. It may be tenable, however, to suspect strong seismic activity on the lateral-slip faults because of their generally greater length and probable greater depth, rather than on the numerous, but in general less extensive, thrust and reverse dip-slip faults.

Geotectonics. The ultimate goal of tectonic researches in southern California's natural laboratory is a contribution to understanding of the mechanisms and causes of earth deformation. It is believed that determinations of slip orientation and cumulative movements on faults will lead to definition of strain pattern, which in turn will lead to definition of stress pattern and eventually to some knowledge of the real causes of crustal mobility.

Tentative answers to these problems, based on facts and interpretations discussed or alluded to in this paper, are: (1) northwest-trending right lateral-slip faults and east-northeast-trending left lateral-slip faults have been active since Jurassic time; (2) these currently active faults probably are genetically related as conjugate shears to establish a primary regional strain pattern of north-south shortening, or relative shortening, of perhaps hundreds of miles; (3) this pattern was caused by forces of as yet unascertained orientation which have been rather consistently operative under this large region for perhaps 100 million years; and (4) sub-crustal convection currents, possibly maintained by heat exchange between sub-Pacific and sub-North American geo-provinces, may be the primary cause of all tectonic deformation in southern California.

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A FAULT MAP OF THE MOJAVE DESERT REGION *

By D. F. Hewett †

INTRODUCTION

Several attempts have been made to compile a map of the known faults in southern California, including the vast Mojave Desert region. The Seismological Society of America prepared such a map in 1923, and in the following year Robert T. Hill presented another fault map of southern California. The geologic map of the State, published by the California Division of Mines in 1938, shows most of the faults that were known at that time. The maps compiled by Harry O. Wood in 1946, mainly to show the epicenters of recent earthquakes, include most of the faults that appear on the geologic map of California.

The map presented herewith (plate 1) was prepared to aid in a program of geologic mapping in the Mojave Desert region that was begun by the Geological Survey in 1947. The first compilation was made in 1951 by Clarence R. Allen, graduate student at the California Institute of Technology, under the supervision of the writer, and it included most of the faults that appear on published geologic maps of the region. Beginning about 1947, air photographs of a large part of the region became available, and since then this type of coverage has become almost complete. It was soon apparent from studies of these photographs that many faults are present in the unmapped areas, and that more faults are present in the mapped areas than have been recorded. Although it is in every sense a preliminary product of field work and office compilation, and hence includes features that need further checking, the new fault map is here offered as a potentially useful summary of existing data.

The principal criteria used for recognition of faults on the air photographs included: (1) Alignment of faceted spurs and small scarps in alluvial fans and playas; (2) Concentration and alignment of desert shrubs and trees in playas and alluvial fans; (3) Alignment of faceted spurs in hard rocks against alluvial fans and playas; (4) Alignment of range fronts discordant with structural features in the hard rocks.

To the assemblage of faults thus recognized have been added the faults discovered on the ground in the areas mapped since the enlarged program of geologic work in the region by the Geological Survey took form in 1952. This paper is the outgrowth of studies involved in the preparation of a general paper on the Mojave Desert region (Hewett, Contribution No. 1, Chapter II), and the reader is referred to this more extensive paper for detailed descriptions, summary illustrations, and a list of references on the geology of the region.

MAJOR OROGENIES OF THE MOJAVE DESERT REGION

Geologic work in the Mojave Desert region that has yielded a published record during the period through 1953 shows that there have been five episodes of major orogenic activity, and that these include the development of thrust faults, reverse faults, strike-slip (tear, lateral) faults, and normal faults that show a wide variety of displacements.

Late Pre-Cambrian Orogeny. The base of the upper pre-Cambrian Pahrump series, as mapped in the northeastern part of the region, rests unconformably upon a wide variety of ancient crystalline rocks. Mapping thus far completed does not reveal any large faults that are assuredly older than the Pahrump series.

Post-Pahrump and Pre-Paleozoic Orogeny. In the Kingston Range and nearby mountains in the northeastern Mojave region, the basal Paleozoic formation (Noonday dolomite) rests unconformably upon the sedimentary rocks of the Pahrump series and upon older crystalline rocks. Mapping has not yet revealed faults older than the basal Paleozoic rocks, although doubtless some are present.

Late Mesozoic (Jurassic and Cretaceous) Orogenies. As stated elsewhere in this volume (Hewett, Contribution No. 1, Chapter II), the pre-Tertiary rocks in the central and western Mojave region were profoundly folded, faulted, and intruded by large bodies of igneous rocks during middle Jurassic time, and in the eastern Mojave region during late Cretaceous time. Thrust faults of large displacement and great areal extent are present in the eastern Mojave region (plate 1), but thus far only one thrust fault, exposed in the Lane Mountain quadrangle, is assuredly known to be associated with this orogeny in the central and western Mojave region.

In the Goodsprings district and Ivanpah quadrangle, a few tear faults are related to the thrust faults, and these are followed by early (premineral) normal faults. Unless they separate rocks of diverse types, such as carbonate rocks and coarsely crystalline rocks, none of the faults of the late Mesozoic orogenies have strong topographic expression; they can only be recognized during the course of areal mapping.

Middle Pliocene Orogeny. Geologic mapping since 1947 within the Mojave block, between the San Andreas and Garlock faults, has shown the existence of basins that contain thick sections of sedimentary rocks of middle and late Miocene age, of early Pliocene age, and of early middle Pliocene age. Estimates of the ages of these rocks are based upon determinations made by G. Edward Lewis of the U. S. Geological Survey, of good collections on vertebrate fossils.

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* Publication authorized by the Director, U. S. Geological Survey.

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The nature of the middle Pliocene orogeny is indicated by the folding of the sedimentary rocks, in which dips of 30°, 40°, and 50° are common and isoclinal folds also are known, and by the presence of many faults. Most of the faults are normal, but several are reverse. Some thrusts are indicated by klippen of much older rocks that rest upon the Tertiary rocks. In the mountains that lie along the east side of the Death Valley-Soda Lake trough for a distance of about 100 miles from the mouth of Furnace Creek on the north to Old Dad Mountain, east of Soda Lake, on the south, mapping has shown the existence of large thrust plates, or klippen. These have been studied and mapped in the Black Mountains by H. D. Curry, in the Virgin Spring area by L. F. Noble, in the Tecopa area by J. F. Mason, in the Silurian Hills by D. H. Kupfer, and in the Shadow Mountains and Kingston Mountains by the writer. Most of the klippen consist of old rocks, mainly pre-Cambrian crystalline types and Paleozoic sedimentary rocks, that rest upon much younger rocks. In some places Tertiary sedimentary rocks lie beneath the thrusts, but in others the overridden rocks are sedimentary beds of the upper pre-Cambrian Pahrump series. Even though the Tertiary rocks that underlie the klippen have not yielded diagnostic fossils, their lithology clearly indicates that they are of Tertiary age, and at present it is assumed that the klippen are features of the middle Pliocene orogeny.

Early Pleistocene Orogeny. In several areas in the eastern and central Mojave region that have been studied and mapped, some large basins are limited by normal faults (Ivanpah Valley, Harper Valley) and numerous linear ranges are bounded by normal faults. The dip displacements along many of these faults are measured in thousands of feet. There has been Recent movement on some of these faults, but it appears that the greatest movement took place in middle Pleistocene time (before deposition of the Manix lake beds). Extensive sheets of fanglomerate of Pleistocene age have been warped in some places, but thus far there is no known evidence of thrust faulting during this epoch.

AREAL GROUPS OF FAULTS

San Andreas Fault. Much is known about the location and nature of movement along the San Andreas fault from San Francisco Bay on the north to the Imperial Valley area on the southeast, or for a distance of about 600 miles. In this paper, the chief concern is for that part of the fault that extends from Tejon Pass, west of Gorman, to Imperial Valley, a distance of about 150 miles. Through the work of M. L. Hill and T. W. Dibblee, Jr., J. C. Crowell, J. H. Wiese, R. E. Wallace, and L. F. Noble, much is known about the local features, nature, and duration of movement along this part of the fault (see Hill, Contribution No. 1, this chapter). The fault is in part a single fracture and in part a group of closely spaced subparallel fractures that define a zone several hundred feet to several miles wide. All observers agree that the fault has had considerable right lateral movement, and hence that the southwest side has moved northwest with respect to the northeast side, which is a part of the Mojave block. Tentative estimates of the horizontal (lateral) movement along the fault range from about 30 miles (L. F. Noble) to a possible 75 miles (R. E. Wallace) since middle Tertiary time, and to as much as 350 miles since Franciscan time (M. L. Hill and T. W. Dibblee, Jr.).

Garlock Fault. The existence of the Garlock fault has been known for at least 50 years, and geologists who have mapped parts of it include J. C. Crowell (Lebec quadrangle), J. H. Wiese (Neenach quadrangle), T. W. Dibblee (Saltdale quadrangle), C. D. Hulin (Randsburg quadrangle), and W. R. Muehlberger (Quail Mountain quadrangle). In places, such as south of Searles Lake, the fault is a single, relatively simple fracture, but for most of its course it is a zone several miles wide. Many small faults and several large ones branch from it.

All geologists who have studied the fault recognize that the dominant Recent movement has been horizontal (lateral, strike-slip). This is revealed by offset stream courses and alluvial fans. In addition, all agree that, during Recent time, the block south of the fault (Mojave block) has moved eastward with respect to the block north of the fault, and hence that left lateral movement has been characteristic. Work done to date also indicates that from the Slate Range southwestward to points near Gorman, the block north of the fault has risen several thousand feet with respect to the block south of it. Thus, the Tehachapi and El Paso Mountains present an abrupt escarpment toward the broad plain of the western Mojave Desert. The north slope of the San Gabriel Mountains, south of the San Andreas fault, forms a similar escarpment toward this plain. Eastward from the Slate Range, however, the situation is reversed along the Garlock fault, as the Avawatz Mountains, south of the fault, present a rugged escarpment that faces northward toward the Death Valley trough and eastward toward the southern extension of this trough, Soda Lake Valley.

Mojave Block. The term Mojave block has been applied to that part of the Mojave Desert region that lies between the San Andreas fault on the southwest and the Garlock fault on the north. The eastern limit of the block will remain uncertain until the southeastern extension of the Garlock fault, beyond Soda Lake, is known. The Mojave block contains many unusual and interesting structural features that differ from, and seem to have little relation to, the features of the areas that lie both to the north and to the south of it.

The geologic features of the Mojave block are discussed elsewhere in this volume (Hewett, Contribution No. 1, Chapter II). A comparison of the distribution, lithology, thickness, and structural features of the Paleozoic and Mesozoic formations within the Mojave block, on the one hand, with these features in corresponding formations in the areas north and south of the block, on the other, indicates that the block was involved in the Jurassic and Cretaceous orogenies but that the Garlock fault did not take form until late in, or after the close of, those orogenies. Soon thereafter the Mojave block began to rise, and by middle Miocene time, when the earliest Tertiary formations were deposited within the block, it had risen at least 15,000 and possibly 20,000 feet with respect to the areas north and south of it. The material eroded from the block during Eocene and Oligocene time seems to have been removed to areas outside the block.

Many faults are known within the Mojave block. If a line is drawn N. 45° W. through a point north of the town of Barstow, roughly at the intersection of 35° north latitude and 117° west longitude, it will divide the block into two parts. The area southwest of this line contains many closely spaced faults, most of which trend northwest or roughly parallel to the San Andreas fault. Most of these faults can be traced for at least 3 miles, several extend 15 to 20 miles, and a few seem to continue for distances as great as 40 miles. The faults in some groups are nearly parallel and in others they have a braided pattern. In the few places where the dips of these faults are observable, they are steep; from the general linear pattern of the faults, the dips of most appear to be greater than 60 degrees.

The approximate dip displacement of many of the faults is known to be several thousand feet; in only a few places is the existence of lateral movement inferred, and it is small compared with the amount of dip movement. Along some of the faults that have been traced for distances of 10 miles or more, the blocks southwest of these faults seem to have dropped with respect to those on the northeast; a few miles away, however, the displacements commonly are reversed. These relations indicate a scissors pattern. At one place, north of Barstow, the relations indicate a reverse fault. In the places where these faults have been studied, they seem to disregard foliation, joint patterns, and bedding planes in the adjacent rocks. The results of Recent movement are noticeable here and there along many of the faults in this part of the block. Geologic mapping does not show that any of the known northwest-trending faults extend to the Garlock fault.

Within the area that lies northeast of the assumed N. 45° W. line, there are only a few proven faults as far north as the Garlock fault. The trend of these faults is diverse, and evidences of Recent movement are rarely observed. Several breaks seem to be traceable for distances of 10 to 20 miles, but most seem to be much shorter.

Flat thrust faults are known on both sides of, but close to, the San Andreas fault and the Garlock fault wherever there has been detailed study, but the thrust displacements seem to be small. In a few places, pre-Tertiary rocks are thrust over Tertiary sedimentary rocks. At two places far from these master breaks and well within the Mojave block, klippen of old rocks rest upon Tertiary sedimentary rocks. Five miles northwest of Barstow, two plates of lower Paleozoic dolomite rest with flat bases upon sedimentary rocks considered to be Tertiary, and a mile southeast of Bitter Spring (east of Camp Irwin), a plate of plicated quartz-mica schist rests with a flat base upon steeply inclined clay and shale that probably are Tertiary in age.

Faults North of the Mojave Block. Much less is known about the geology of the region that lies north of the Garlock fault as far east as the Death Valley trough than is known about areas south of the fault. The region east of Death Valley, in contrast, has been more extensively studied, and much of the geology in the Black Mountains, the Virgin Spring area, the Tecopa quadrangle, and the large area east of the Silver Lake-Soda Lake valley (Ivanpah quadrangle) is a matter of published record.

Existing information indicates that an impressive fault zone is essentially coextensive with the eastern front of the Sierra Nevada, and there has been Recent movement at several places in Owens Valley. Farther east, recent work west and northwest of Searles Lake has shown the presence of several small faults of northwest trend in the Argus Range, and seismic work east of the lake indicates that there may be a fault parallel to the west border of the Slate Range. Searles Lake basin has been closed in Recent time by movement on the Garlock fault.

Impressive faults mark the west slope of the Panamint Range, and Panamint Valley has been closed in Recent time by movement along the Garlock fault. At the south end of the Panamint Range, a group of faults curves southeastward around Brown Mountain and joins the Garlock fault zone near Leach Spring.

Small faults that show Recent movement are present on both the west and east sides of Death Valley, and the valley itself must coincide with a fault zone of great displacement, as the east slope of the Panamint Range shows a section of Paleozoic sedimentary rocks at least 25,000 feet thick that dips eastward into the valley. No similar sedimentary rocks are known to the east between the valley and the Funeral Mountains, and the intervening Black Mountain Range is made up of lower pre-Cambrian crystalline rocks upon which have been thrust great plates that consist largely of Tertiary sedimentary rocks (see Curry, Contribution No. 7, this chapter).

Faults East of the Death Valley-Silver Lake-Soda Lake Troughs. In the Ivanpah quadrangle, the late Mesozoic orogeny produced great thrust faults, five of which have been traced many miles. In the intervening areas, the Paleozoic and Mesozoic sedimentary rocks have been compressed into open folds and locally into close folds with some overturned beds. Several of the thrust faults have been traced northward beyond 36°00′ north latitude, but none are known south of Kelso Wash.

Normal faults exposed in the Ivanpah quadrangle seem to be concentrated around Ivanpah Valley, the floor of which almost coincides with a block that has been dropped about 20,000 feet. Most, if not all, of this depression seems to have taken place in early Pleistocene time, after development of the Ivanpah Upland (Hewett, Contribution No. 1, Chapter II). Mapping in the Providence Mountains by J. C. Hazzard (Contribution No. 4, this chapter) indicates many small faults but no thrust faults; one steep reverse fault lies along the east margin of the range. South and east of the Providence Mountains there has been little geologic mapping, but the form of some of the ranges suggests that they are bounded by normal faults. The linear southwest fronts of the Granite and Marble Mountains suggest that they coincide with persistent northwest-trending normal faults; if this proves to be the case, these faults are the most eastern of the group in the region.

Close examination of air photographs of the region east of 116°00′ west longitude, supplemented by brief field reconnaissance, does not reveal faulted fans and playas that would indicate that the faults in this region are active.

INTERPRETATION OF THE FAULTS OF THE REGION

Although little is known about many of the faults that are shown in plate 1, the existence and nature of others are well understood. In the areas that have been studied and mapped geologically, much information is available concerning direction and amount of movement on numerous faults during Pleistocene and Recent time. It seems doubtful that further studies of these faults would greatly change present interpretations. Several conclusions seem dependable at this time:

1. The San Andreas fault seems to be relatively old, and there seems to have been movement along it prior to the orogenies of late Mesozoic (Jurassic and Cretaceous) time.

2. From the distribution, lithology, thicknesses, and deformation of the Paleozoic and Mesozoic formations, even though much remains to be learned about them, it appears that throughout the entire Mojave region these formations were folded along generally north-south axes, and that in the eastern part of the region at least five great thrust faults were formed. As about the same kind and degree of deformation characterizes the rocks both north and south of the Garlock fault, this fault was probably not formed until late in the Mesozoic orogeny or shortly after it closed.

3. Before any Tertiary sedimentary rocks were deposited within the Mojave block, it had risen 15,000 or 20,000 feet, and had been eroded as it rose; undoubtedly it stood above the nearby areas until Miocene time.

4. The oldest Tertiary sedimentary rocks in the Mojave block are of middle Miocene age, and the several basins contain sections, 3,000 to 10,000 feet thick, of middle and late Miocene age, of early Pliocene age, and of early middle Pliocene age.

5. Following the deposition of the youngest Tertiary sedimentary rocks, which are early middle Pliocene in age, the entire region was involved in an orogeny that produced folds, mostly open but in a few places isoclinal, and sporadic thrust faults within the block, as well as great thrust faults along the northeastern and eastern margins of the block. These are now represented by the plates on the turtlebacks in the Black Mountains, by the chaos of the Virgin Spring area, and by the great plates of the Kingston Range, Shadow Mountains, Silurian Hills, and Old Dad Mountain.

6. The distribution, direction, and local pattern of the northwestern group of northwest-trending faults in the Mojave block, as well as their disregard for the lithology, stratification, foliation, and jointing of the rocks they cut, all indicate that these faults were formed during a period of great lateral pressure, probably during Eocene and Oligocene time, when the block was rising and before deposition of the earliest Tertiary sedimentary rocks. There may have been additional movement along these northwest-trending faults during the middle Pliocene orogeny.

7. Renewed local movement on the northwest group of faults, largely during early Pleistocene time but continuing to the present, has determined the principal mountains and valleys of the southwestern half of the Mojave block. Probably most of the mountains that lie east of the block took form at this time, but little evidence to support this conclusion is yet at hand.

3. SEISMICITY OF SOUTHERN CALIFORNIA*

BY CHARLES F. RICHTER † AND BENO GUTENBERG ‡

Evidence for regional seismicity is of four kinds: (1) geological field observation of fault phenomena, (2) historical documents, (3) instrumental recording, and (4) field investigation immediately after earthquakes.

Historical and instrumental data cover a very small part of geological time, and thus constitute only a snapshot of the record, so to speak. They may furnish positive evidence of seismicity, but failure of earthquakes to occur on a given fault during a period of less than two centuries is no proof of quiescence. On the other hand, identifying faults as active on the basis of field evidence alone implies an assumption that there have been no significant permanent changes in seismicity in a few tens of thousands of years. This assumption is reasonable, but it does not necessarily apply without exception.

Faults are commonly identified as active on the basis of such field evidence as small scarps, especially if these cut young alluvial fans; slickensides in modern deposits; offsets in minor drainage channels; and sag ponds. There are differences, however, in the apparent age of these features. Many small features along the San Andreas fault are very fresh in appearance, and are known or believed to have originated during the earthquakes of 1857 and 1906. The rift topography along the Garlock fault includes many sag ponds, low scarps, and other geologically young features, but relatively few of these seem to be truly fresh. This suggests that no major earthquake has broken the surface along the Garlock fault within the last few centuries.

Known occurrences of fault-trace phenomena associated with recorded earthquakes in southern California are: (1) *January 9, 1857.* San Andreas fault, from Carrizo Plain to San Bernardino, and possibly farther in both directions; (2) *March 26, 1872.* Owens Valley; faulting, chiefly vertical with some strike-slip movement, along the line of the east front of the Alabama Hills (not along the major Sierra Nevada scarp several miles west); (3) *March 10, 1922.* San Andreas fault in the region of Cholame; large cracks, possibly not primary fault-trace effects; (4) *May 18, 1940.* Imperial Valley; fault trace at least 40 miles long, extending from the vicinity of Imperial and Brawley southeastward into Mexico; right-hand strike-slip movement, reaching a maximum displacement of 19 feet near the international boundary; scarps as much as 4 feet high; (5) *April 10, 1947.* Southeast of Manix, Mojave Desert; left-hand strike-slip movement of only a few inches along the line of the Manix fault; instrumental locations of epicenters of aftershocks aligned nearly at right angles to this fault, suggesting that the observed displacement is a secondary result of a larger displacement on a fault with different strike in the basement rocks; (6) *July 21, 1952.* Arvin-Tehachapi earthquake, Kern County; probably thrust faulting, with surface expression obscured and complicated by large-scale slumping and sliding; White Wolf fault.

The historical record begins with a strong earthquake felt by the Portola expedition on July 28, 1769, when the explorers were in camp along the Santa Ana River near the present townsite of Olive. Subsequent information for all of California is extremely scanty until 1850, and in southern California the record is imperfect for an even longer period of time. Especially in the desert areas, even a major earthquake could have escaped notice until about 1887, when the seismological station at Lick Observatory was established. In this same year the first catalogue of California earthquakes was published.

The greater earthquakes known to have occurred in the region of California and Nevada are: (1) *January 9, 1857,* San Andreas fault (see above); (2) *March 26, 1872,* Owens Valley (see above); (3) *April 18, 1906,* San Andreas fault: epicenter north of San Francisco; instrumental magnitude 8¼; (4) *October 1, 1915,* Pleasant Valley, south of Winnemucca, Nevada; instrumental magnitude 7¾; (5) *July 21, 1952,* Kern County; instrumental magnitude between 7½ and 7¾ (investigation in progress).

Several less well known shocks, as those in 1812, 1836, 1838, 1852, and 1868, may have been comparable with these.

California forms a small part of the circum-Pacific belt of seismic activity (figs. 1, 2), which accounts for roughly 80 percent of the seismicity of the earth. Of this, southern California contributes between ½ and 1 percent. Most of the circum-Pacific belt is composed of arcuate structures that are associated with deep as well as shallow earthquakes, very active volcanism, folding, and thrust faulting. California is the largest of several sectors in which the structures are not evidently arcuate, where only shallow earthquakes occur, and where the tectonics are primarily those of block faulting, including long, narrow rift zones associated chiefly with strike-slip faults.

In evaluating both historical and instrumental data, due attention should be paid to magnitude of the earthquakes. Frequently a comparatively moderate earthquake, such as the Long Beach earthquake of 1933, chances to originate in a thickly populated area and hence

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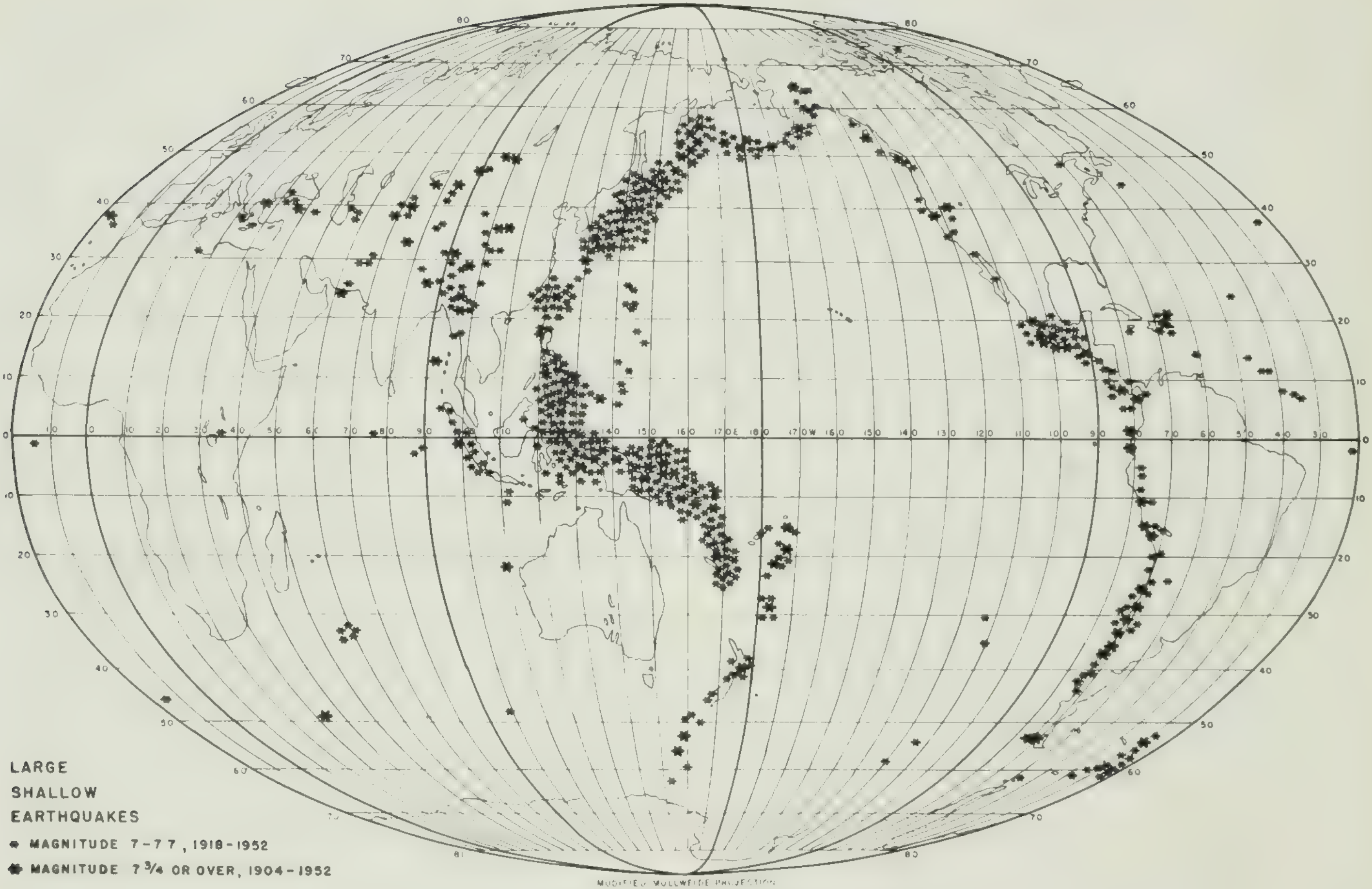
LARGE
SHALLOW
EARTHQUAKES
● MAGNITUDE 7-7.7, 1918-1952
✱ MAGNITUDE 7¾ OR OVER, 1904-1952
MODIFIED MOLLWEIDE PROJECTION

FIGURE 1. Large shallow earthquakes of the world, 1904-52.

Epicenter location, origin time, and magnitude of some of the shocks shown in figure 2.

Date	Time	Latitude	Longitude	Magnitude
1934, June 8	04:47:45	36 N	120½ W	6.0
1952, Nov. 22	07:46:38	35.8 N	121.2 W	6 ±
1922, March 10	11:21:20	35¾ N	120¼ W	6½
1946, March 15	13:49:36	35.7 N	118.1 W	6¼
1952, July 21	11:52:14	35.0 N	119.0 W	7.7
1947, April 10	15:58:06	35.0 N	116.6 W	6.4
1916, Oct. 23	02:44	34.9 N	118.9 W	5½ ±
1927, Nov. 4	13:50:43	34½ N	121½ W	7.3
1946, July 18	14:27:58	34.5 N	116.0 W	5¾
1941, July 1	07:50:55	34.4 N	119.6 W	5.9
1925, June 29	14:42:16	34.3 N	119.8 W	6¼
1930, Jan. 16	00:24:34	34.2 N	116.9 W	5¼
1935, Oct. 24	14:48:08	34.1 N	116.8 W	5¼
1940, May 18	05:03:59	34.1 N	116.3 W	5.4
1923, July 23	07:30:26	34 N	117¼ W	6¼
1947, July 24	22:10:47	34.0 N	116.5 W	5.5
1949, May 2	11:25:47	34.0 N	115.7 W	5.9
1930, August 31	00:40:36	33.9 N	118.6 W	5¼
1948, Dec. 4	23:43:17	33.9 N	116.4 W	6.5 ±
1941, Nov. 14	08:41:36	33.8 N	118.2 W	5.4
1933, Oct. 2	09:10:18	33.8 N	118.1 W	5.4
1918, April 21	22:32:25	33¾ N	117 W	6.8
1933, March 11	01:54:08	33.6 N	118.0 W	6¼
1937, March 25	16:49:03	33.5 N	116.5 W	6.0
1942, Oct. 22	01:50:38	33.3 N	115.7 W	5¾
1950, July 28	17:50:48	33.1 N	115.6 W	5.4
1950, July 29	14:36:32	33.1 N	115.6 W	5.4
1942, Oct. 21	16:22:14	33.0 N	116.0 W	6½
1951, Dec. 26	00:46:54	32.8 N	118.3 W	5.9
1940, May 19	04:36:41	32.7 N	115.5 W	6.7
1948, Feb. 24	08:15:10	32.5 N	118.5 W	5.3
1927, Jan. 1	08:16:45	32½ N	115½ W	5¾
1927, Jan. 1	09:13:30	32½ N	115½ W	5½
1935, Feb. 24	01:45:10	32½ N	115 W	5¼

does much more damage and attracts more general attention than major earthquakes, like those in Nevada in 1915 and 1932, which center in remote and sparsely populated areas. The instrumental magnitude scale, set up in 1932, defines the magnitude of a given earthquake as the logarithm of the trace amplitude, in units of 0.001 mm, as measured on the seismogram written by a specified standard instrument at a distance of 100 kilometers from the epicenter. For other distances, or for instruments of other types, reduction to the standard is accomplished by means of appropriate tables and computations. With due allowance for known local effects at the individual stations, magnitudes determined for the same earthquake at different stations are in good agreement, so that magnitudes commonly are assigned to the nearest tenth or quarter of a unit. The smallest instrumentally observed earthquakes are near the zero of the scale and the largest known are of magnitude 8.6. These numbers are not those of the commonly used local intensity scales, which rate the field effects (damage to structures, effects on terrain, etc.) in terms of an arbitrary scale ranging from I to XII. High intensity may result because an earthquake of moderate magnitude originates nearby or because an earthquake of large magnitude originates at a distance.

Some results of experience with the magnitude scale can be tabulated as follows:

Magnitude	Effects
1	Only observed instrumentally.
2	Can be barely felt (intensity II) near epicenter.
4½	Felt to distances of some 20 miles from the epicenter; may cause slight damage (intensity VII) in a small area.
6 +	Moderately destructive (example: Long Beach, 1933; Santa Barbara, 1925).
7 +	Major earthquake.
7¾ +	Great earthquake (1872, 1906).

Because of the late development of instrumental seismology, great earthquakes of magnitude 8 and over can be catalogued completely only for the period beginning in 1904 (fig. 1). Such earthquakes are related to the major active structures. Minor earthquakes, on the other hand, are more commonly related to minor faults and structures, and the epicenters of the small, instrumentally recorded shocks are peppered over the region.

Since 1932, epicenters for sufficiently well recorded shocks have been assigned from the data of the seismological network in southern California. This record includes most earthquakes of magnitude 3 and over, but with notable imperfections in the data for some shocks, particularly those about the margin of the area. A map showing such small shocks for the whole region is nearly certain to give a false impression; for example, these results have sometimes been misinterpreted as indicating relatively low seismicity in the offshore and island area to the southwest, an area that is comparatively remote from most of the established stations, and that is in a bad position for accurate locations. Figure 3 shows located shocks of magnitude 4½ and over, for the period 1934-51.

Figure 2, showing California and other western states, includes no shocks of magnitude under 5¼; those shown are consequently large enough to be recorded at distant stations. It is clear that a continuous belt of seismicity, continuous but irregular in detail, extends from the region of the north coast, the most active part of the entire region, southeastward and through the Gulf of California. The chief seismic zone widens south of the Transverse Ranges, owing to the branching of the San Andreas fault, and to the occurrence of other parallel active faults.

The earthquakes of the Great Basin and the Rocky Mountain regions, though occasionally large, are comparatively sporadic in occurrence and in geographical distribution.

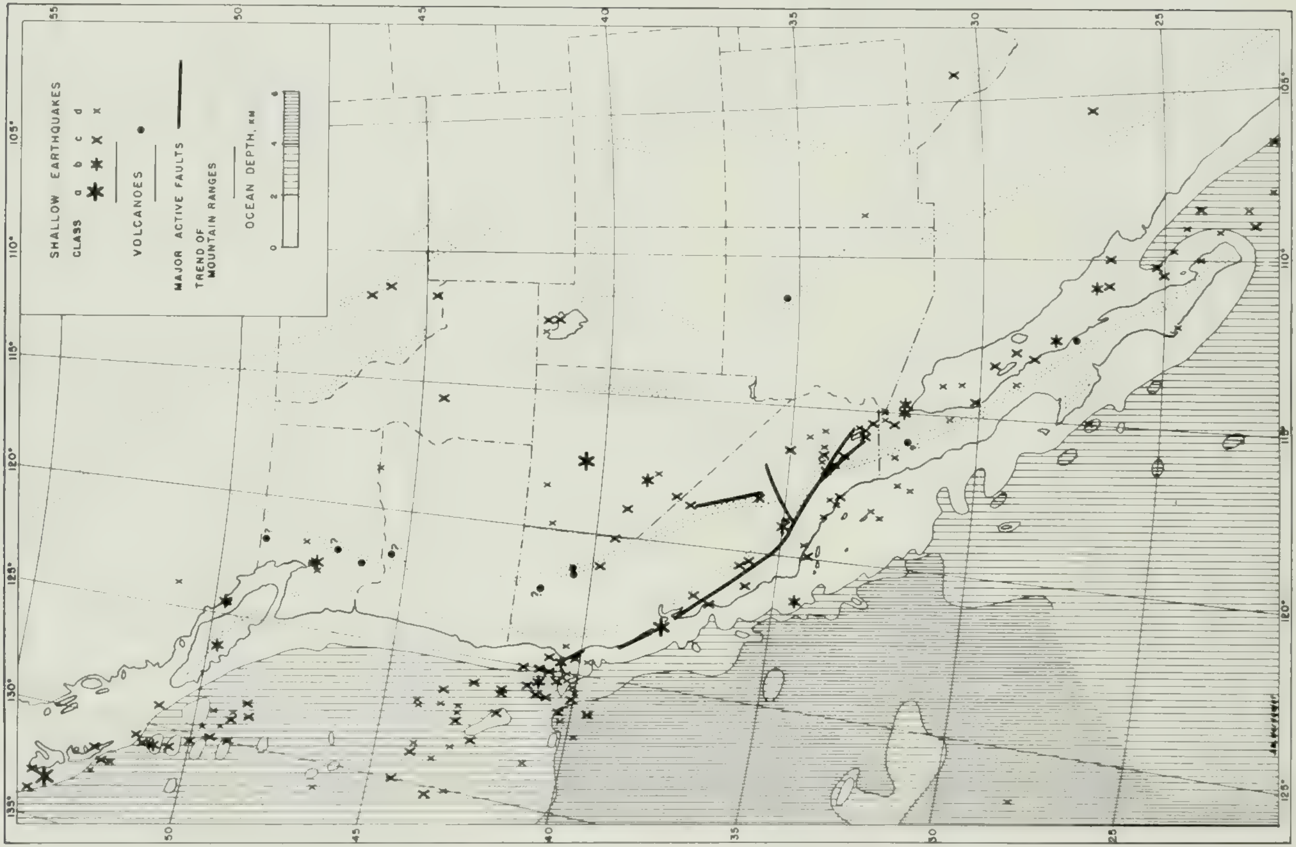

FIGURE 2. Seismicity of the Cordilleran United States and adjacent areas.

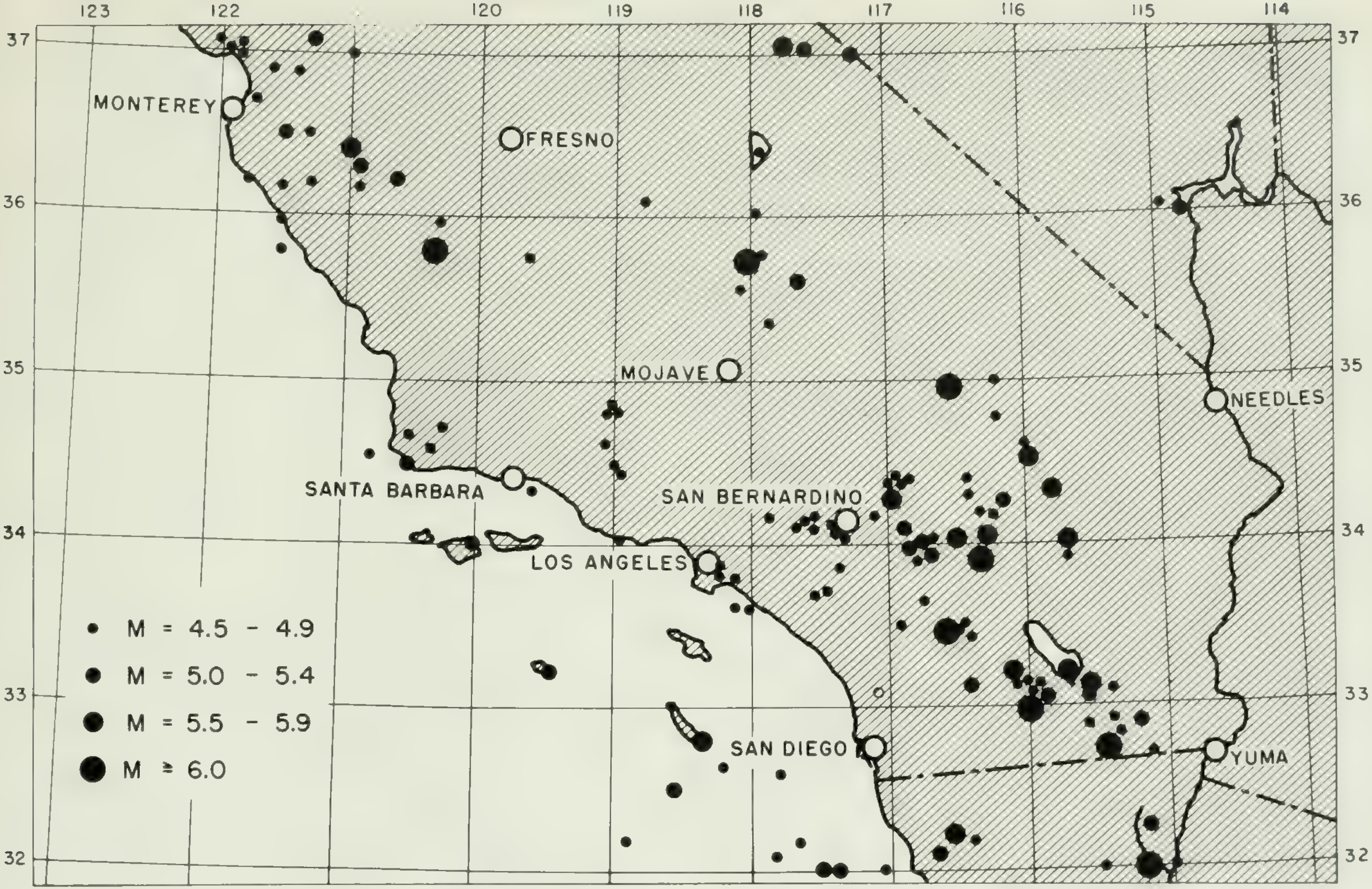

FIGURE 3. Earthquakes of magnitude 4.5 and over, southern California, 1934-51.

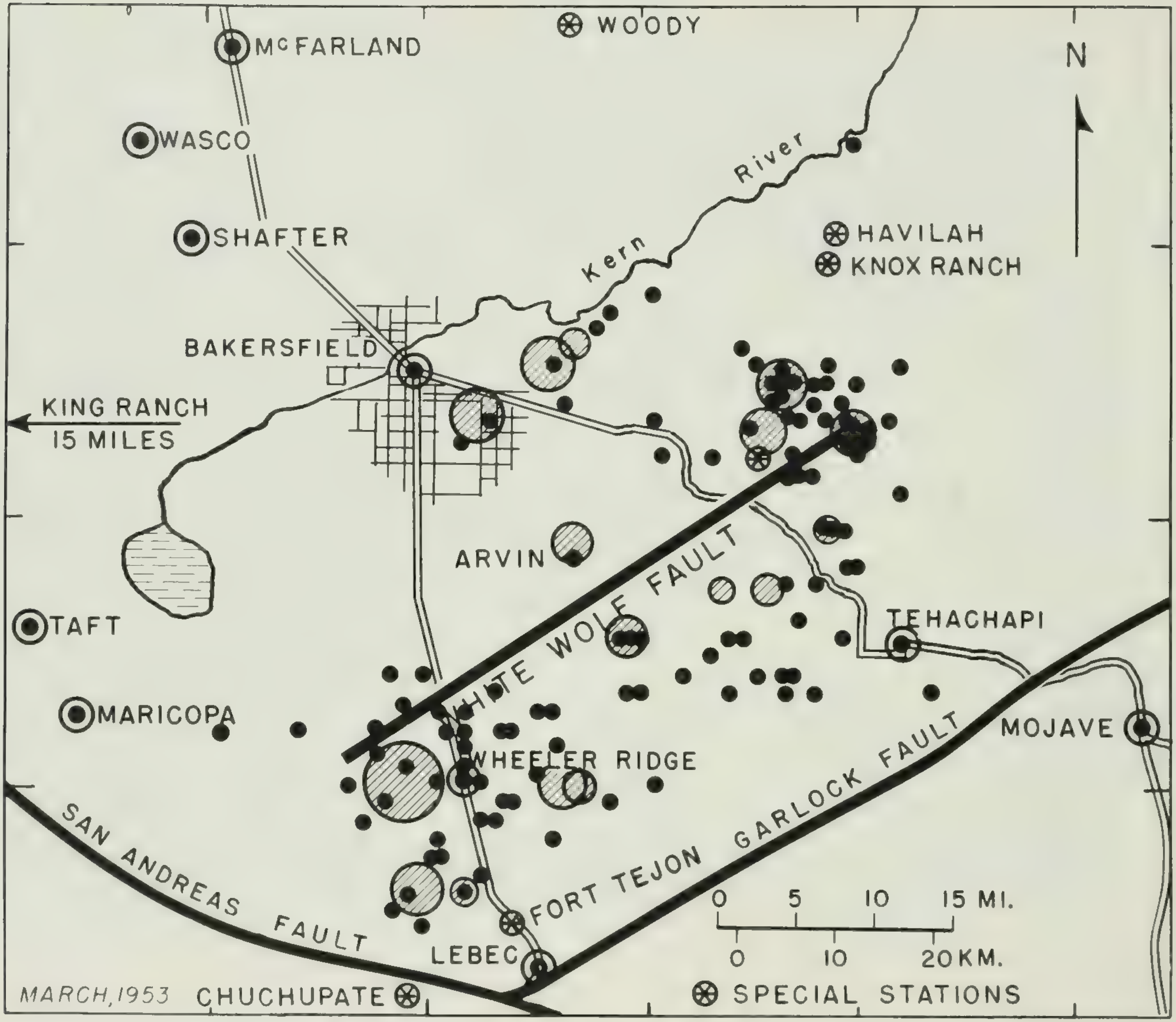

FIGURE 4. Kern County earthquake series, 1952. (See text for explanation of symbols.)

The accompanying table gives epicenter and origin time for those shocks shown in figure 2 between latitudes 32°30′N and 36°00′N.

For shocks such as those of 1906, 1940, and 1952, where there is notable linear extent of faulting, the instrumental epicenter is above the point of initial rupture, because this is the point of origin of the first seismic waves to be recorded at a given station. Not uncommonly, as in 1933 and 1952, the epicenter lies at one end of the active fault segment, and consequently is eccentric with respect to the heavily shaken area, and to the geographical distribution of aftershocks (fig. 4).

The location of almost every epicenter shown in figures 3 and 4 may be in error by 5 miles or even more. Great care should be exercised in using seismological data to discriminate between activity of closely spaced faults. A comparatively small difference in dip will have considerable effect on the relation of epicenter to surface trace, as the average depth of the hypocenter (the actual point of initial rupture, directly beneath the point mapped as epicenter), is about 10 miles.

In routine epicenter-location work at Pasadena, which involves determinations for about 250 local earthquakes each year, it has been customary to assign a fixed depth of origin of about 10 miles for southern California shocks, unless the available data clearly conflict with that assumption. This sometimes has been taken to mean that all southern California earthquakes originate at nearly the same depth. This is certainly not so; some probably originate at points as deep as 15 miles, and others at points within 5 miles of the surface.

At the present writing, no conclusions safely can be drawn if they depend very delicately on seismological assignments of hypocentral depths. Observations during the last few years have led to significant revision of interpretation for recorded seismic waves at short epicentral distances. This revision affects epicenters and depths to some extent, within the ranges mentioned above. Investigation is still in progress, and the course it takes will be materially affected by the unusually accurate and copious data obtained for the Kern County earthquakes of 1952.

Figure 4 shows epicenters determined for the larger shocks of the Kern County series. Those of magnitude 5 and over are indicated by shaded circles; there are 22 of these, and the listing is complete. Those of magnitude 4-5 are indicated by smaller solid spots, which include all epicenters whose locations had been worked out by the end of 1952. Some repetitions in location are not indicated separately. In addition, many more shocks were recorded. About 50 of them, for example, are estimated to have taken place within the first 3 hours on July 21, and locations for these are difficult, if not impossible to work out because of overlapping recordings. The much more numerous shocks of smaller magnitude are largely uninvestigated.

The location of the aftershock epicenters shows a significant progression in time. Aftershocks are known to have occurred along the entire active segment of the White Wolf fault, from the principal epicenter to a point near Caliente, for the first 36 hours; but all these aftershock epicenters lie southeast of the surface trace of this fault, and thus are consistent and compatible with a dip in that direction. After 36 hours, shocks began to occur northwest of the surface trace. On July 29, a series of shocks began with epicenters distributed along a line extending roughly northeastward from Bakersfield, and approximately parallel to the trace of the White Wolf fault. This series included a shock on August 22, which, though of magnitude no greater than about 5.6, was so close to Bakersfield that it caused more damage there than the principal earthquake of July 21. The alignment of these epicenters crosses folds and other structures exposed at the surface, which in that area trend more nearly northwest. This result recalls the relation of the Manix fault to the epicenters of the Manix series of shocks, and suggests a deep, active structure that possibly may be related to the canyon of the Kern River in that vicinity.

These results probably do not represent any unusual complexity. Our information on this occasion is exceptionally full, and is adequate to establish phenomena that probably are characteristic of most major events of the kind.

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4. ROCKS AND STRUCTURE OF THE NORTHERN PROVIDENCE MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

By John C. Hazzard *

INTRODUCTION

General Statement. The area herein described covers about 50 square miles in the northern Providence Mountains of San Bernardino County, California. The major part of the area shown on the geologic map (plate 2) lies west of west longitude 115° 30′, within the Ivanpah and Amboy quadrangles. The Providence Range is bordered on the west by Kelso Valley, through which the Union Pacific Railroad passes, and the eastern front of the mountains faces on a lobe of Fenner Valley, through which a good graded gravel road connects Mitchell's Caverns at the mountain base with Essex on U. S. Highway 66. Foshay Pass, which lies between the northern and southern portions of the Providence Range, offers the shortest route from one side of the mountains to the other, but the road is not maintained.

Published references to the geology of the Providence Range are few. The best summary up to 1929 is that given by Thompson (1929), who also presents an historical sketch of the Mojave Desert region and an excellent review of its water supply, flora, and fauna. Most of the mines in the region are mentioned in various reports of the California State Mineralogist. A list of selected references to the northern Providence Mountains and geologically related areas is presented at the end of this paper.

During progress of the mapping in the northern Providence Mountains and during the preliminary preparation of this paper, certain of the results were published as abstracts or short papers (Hazzard, 1933, 1937a, 1937b, 1938a, 1941; Hazzard and Mason, 1936; Thompson, Wheeler, and Hazzard, 1946). For this reason, and because of space limitations necessarily placed upon this paper, an attempt has been made to present the salient stratigraphic and paleontologic features of the range as a tabular summary (table 1) which obviously does not allow detailed lithologic description or full discussion of correlation problems. The positions of several measured stratigraphic sections are shown on the geologic map (plate 2). These sections furnished many of the stratigraphic data presented in the tabular summary and in some of the earlier publications on the area. The reported fossil localities are not the only places where fossils were found, but are believed to be representative of the best collecting localities.

Field Work and Acknowledgments. The field work upon which this paper is based was started in 1932, and was continued during parts of each summer field season through 1936. Since then the writer has visited the area at various times in quest of additional paleontological and stratigraphic data.

The only base maps of the northern Providence Mountains that were available in 1932 were the U. S. Geological Survey map of the Ivanpah quadrangle, on a scale of 1/250,000, and a map surveyed by the Metropolitan Water District of southern California prior to construction of the Colorado River aqueduct. The latter map was published in 1942, on a scale of 1/250,000, by the Army Map Service as the Amboy quadrangle. Inasmuch as neither of these maps is on a scale large enough to allow the delineation of much geologic detail, the writer mapped the area of interest by plane-table methods on a scale of 1 inch to 2,000 feet. This program was carried on through three field seasons, during which approximately 3,200 rod stations were occupied. Elevations shown in plate 2 are those established during the survey, and are based on bench marks along the Union Pacific Railroad.

To Miguel de Laveaga, William T. Roeseler, and F. Maclin Carlisle the writer is indebted for assistance as instrument men. Dion L. Gardner, John F. Mason, and William T. Rothwell assisted in the field at various times. Thanks are due G. Arthur Cooper, Colin Crickmay, William H. Easton, J. Brooks Knight, John F. Mason, Charles W. Merriam, Siemon W. Muller, A. R. Palmer, Charles E. Resser, and M. L. Thompson for examination of fossil collections, and Cordell Durrell for his study of several thin sections of the igneous rocks. Many residents of the Providence Mountains region assisted the writer in various ways. Special thanks are extended to Mr. and Mrs. Clifton Barnes, formerly of Pine Tree Ranch, and to Mr. and Mrs. Jack Mitchell of Mitchell's Caverns. For two field seasons financial assistance was provided by the California State Division of Mines. Between 1950 and 1952, three visits were made to the Providence Range in connection with stratigraphic studies in the Great Basin region for the Union Oil Company of California.

PHYSIOGRAPHY

The northern Providence Mountains have a north-south dimension of about 8½ miles between Foshay Pass and Summit Springs, and a maximum width of about 7 miles. Foshay Pass, about 9 miles southeast of Kelso, is both a marked physiographic feature and an important geologic boundary. Paleozoic sedimentary rocks and Tertiary intrusive rocks compose the major part of the mountain area north of the pass; pre-Cambrian and younger crystalline rocks underlie

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Table 1. Summary of rock units exposed

AGE	FORMATION	MEMBER	LITHOLOGIC CHARACTER	THICKNESS (Feet)		CONTAINED FOSSILS TYPICAL FORMS
QUATERNARY	Alluvium and landslide deposits		Unconsolidated sand, gravel, and boulders of local origin.			
	Unconformity					
	Terrace gravels		Moderately consolidated fanglomerate. Character dependent on lithology of source.	75 ±		No fossils found
	Unconformity					
	Limestone breccia		Rudely bedded, well-cemented limestone breccia. Fragments subangular; maximum size observed about 5 feet; average size of coarser material between 6 inches and 1 foot. Material under 6 inches in diameter composes about 50 percent of mass. Possibly of landslide origin.	75–150+		No fossils found
	Unconformity					
TERTIARY Miocene (?)			Principally andesitic or dacitic tuffs including crystal-vitric, crystal-lithic, and vitri-lithic types. Colors range from dark gray to white and dark to light reddish brown. Some units are massive, others well bedded. Andesitic and basaltic flow rocks are estimated to compose one-quarter of the section. Water-laid tuffaceous sands occur, and locally at the base of the section there are limestone cobble conglomerates and tuffaceous lacustrine limestone.	1100–1200 (max.)		*Sequoia langsdorfi* Ostracods
	Unconformity					
LOWER TRIASSIC	Moenkopi formation	Four lithologic members recognized	(4) Light and dark gray nodular limestone; some shale.	470+	1000	*Monotis thaynesiana* *Pseudomonotis* cf. *P. hinnitidea* *Myophoria* cf. *M. curvirostis* *Stephanites* sp. *Subcolumbites* sp. (Ref. 6)
			(3) Olive-drab, platy to paper-thin clay shale and dark gray fossiliferous limestone.	155		
			(2) Light gray to tan, commonly buff-weathering fossiliferous limestone, in part sandy and shaly.	155		
			(1) Maroon and reddish-buff to brown sandstone, with reddish and maroon clay shale and limestone pebble conglomerate.	217		
	Unconformity					
PERMIAN	Bird Spring formation (Ref. 13, 18) (Note 5) Includes rocks of Wolfcamp and probably Leonard age (Ref. 23)		At the base is a 20-foot zone of locally cross-bedded sandy limestone and limy sandstone with black chert pebbles. About 75 feet above is a massive 70-foot light gray limestone. As a unit the lower 750 feet of beds consists of dark and light gray limestone in beds up to 10 feet thick. Platy to shaly, in part sandy, fossiliferous, chert-rich zones separate some of the massive beds. The upper 1380 ± feet of the section is medium to light gray, sparingly fossiliferous limestone in beds up to 5 feet thick. Minor chert and sandstone occur.	2130+	2935 ±	MEGAFAUNA includes: *Thysanophyllum* n. sp., *Syringopora* sp., *Striatopora* sp., *Echinocrinus* sp., *Fenestrellina* sp., *Derbya* sp., *Dictyoclostus americanus*, *Neospirifer* aff. *N. condor*, *Composita* sp., *Leiorhynchoidea* cf. *L. laevis*, *Spiriferellina* cf. *S. hilli*, *Omphalotrochus* sp., *Aclisina* ? sp., *Donaldina* sp. MICROFAUNA includes species of the following: *Parafusulina*, *Schubertella*, *Schwagerina*, *Pseudoschwagerina*, *Triticites*, and *Dunbarinella*
PENNSYLVANIAN			Very dark to light creamy gray limestone, locally dolomitized. Lower half of unit comprises massive-weathering beds up to 30 feet in thickness separated by platy, commonly cherty and fossiliferous layers. Minor amounts of sandstone, sandy limestone, and shale occur. Outcrop surface commonly develops a cliff-bench slope.	825		*Dictyoclostus portlockianus*, ? *Enteletes hemiplicatus*, *Juresania nebrascensis*, *Marginifera muricatina*, *Spirifer* cf. *S. opimus*, *Gastrioceras* cf. *G. cancellatum*, *Griffithides* sp.
	Unconformity					
MIDDLE MISSISSIPPIAN	Monte Cristo limestone (Ref. 13)	Yellowpine limestone	Very dark gray limestone; generally massive but locally thinly bedded.	75–125	700-880	*Caninophyllum* sp.
		Bullion limestone	Light gray to cream-colored crinoidal limestone with very obscure bedding. Commonly cliff-forming.	250–350		
		Anchor limestone	Light gray, platy-weathering crinoidal limestone with much brown chert in irregular nodules and sheets along bedding planes.	100–150		Fenestellid and other Bryozoa, Crinoid stems, *Triplophyllites* sp., *Homalophyllites* sp., *Dielasma* sp., *Derbya* sp., *Productus* sp., *Spirifer centronatus*, *Spirifer* cf. *S. Logani*
		Dawn limestone	Light and dark gray limestone in massive beds up to 20 feet thick separated by platy beds. Upper part characterized by much chert in irregular, discontinuous beds up to 3 inches in thickness.	240		
		Basal sandstone	White to brownish-weathering vitreous quartzite and sandstone with local cross-bedding.	10–15		
	Unconformity					

References on pp. 34-35.

in the northern Providence Mountains.

CONTAINED FOSSILS FOSSIL LOCALITIES (*See* Geologic Map)	SUGGESTED CORRELATION	ECONOMIC VALUE	UNCONFORMITIES
			Along Hayden Wash the breccia rests on the pre-Cambrian complex on an erosion surface with a relief estimated as great as 100 feet. Relation of the breccia to other units of geologic column is unknown. Major portion of limestone composing the breccia is from upper part of Paleozoic section.
Near Beecher Spring east of 7-I-L (Domingo) Ranch In canyon north of Good Hope mine		Tuffs could be used for building stone	In Fenner Valley and Wild Horse Mesa the volcanic sequence rests on an erosion surface having as much as 200 feet of relief cut across pre-Cambrian and younger crystalline rocks. At the north end of Providence Range the limestone-cobble conglomerate at base of volcanic section indicates that west of the East Providence fault Paleozoic rocks cropped out as a mountain ridge in pre-Miocene (?) time. On the northwest side of Fountain Peak bedded volcanic sediments and tuffs lie unconformably on Lower Triassic Moenkopi formation.
Measured section T-T′	Moenkopi formation of the Goodsprings quadrangle, Nevada (Ref. 13).		Beds appear essentially conformable; major part of contact is faulted. Magnitude of break established by regional relations. In the Goodsprings quadrangle, Nevada, is 1600+ feet of Permian beds that do not occur in the Providence Mountains (Ref. 13).
Measured sections P_1-P_1', P_2-P_2', P_3-P_3', and localities, P-608, P-627, P-1189-A, P-1189, P-1210-A, JCH 2010.	Upper portion of Bird Springs formation, Goodsprings quadrangle, Nevada (Ref. 13, 18).	(1) Mineralized along the East Providence fault in vicinity of Mitchell mine. (2) Possibly mineralized on north side of Foshay Pass. (3) Altered to marble south of Mitchell's Caverns and on north side of Foshay Pass. (4) Mitchell's Caverns developed in this unit.	
			(*See* Note 5)
Loc. P-1198, P-1494-A	(1) Lower portion of Bird Springs formation, Goodsprings quadrangle, Nevada (Ref. 13). (2) Bird Springs formation, Nopah Range, California (Ref. 10).	(1) Slightly mineralized just west of Bonanza King mine. (2) Mineralized along East Providence fault in vicinity of C. and K. (McGilroy) mine. Values in Ag and Pb.	
			(*See* Note 5)
Loc. P-1189-B, P-1223, P-1359, P-1545	(1) Monte Cristo limestone of the Goodsprings quadrangle (Ref. 13). (2) Monte Cristo limestone of the Nopah Range (Ref. 10).		
			Beds appear conformable; no angular discordance observed. Basal sandstone contains pebbles and cobbles of limestone; surface of underlying beds is irregular, with sand-filled "pot-holes" up to 18 inches deep and 1 to 2 feet across; sand filling is rudely bedded. Stratigraphic value of unconformity not established.

Table 1. Summary of rock units exposed

AGE	FORMATION	MEMBER	LITHOLOGIC CHARACTER	THICKNESS (Feet)			CONTAINED FOSSILS
							TYPICAL FORMS
MIDDLE DEVONIAN	Sultan limestone (Ref. 13)	Crystal Pass limestone	Light creamy gray porcelain-like limestone in beds 4 to 10 feet thick.	250-300		925-1075	
		Valentine limestone	Light and dark gray limestone in massive beds as much as 10 feet thick, alternating with thin-bedded to platy layers. Two thin sandstone beds in basal portion. Dolomitization of lower portion is common.	350-400	550-600		*Stromatopora* sp., "*Cyathophyllum*" *flexum* ?, *Disphyllum lonense* ?, *Platyschisma ambigum*
			Dark gray and buff-weathering dolomite in beds 6 inches to 2 feet thick. About 100 feet above the base is a 25-foot very dark smoky gray dolomite resembling the Ironside (?) member.	200+			
		Ironside(?) dolomite	Very dark smoky gray dolomite with nests and bunches of coarse crystals of white dolomite.	50-75			
		Basal dolomite and sandstone	Light and dark gray dolomite, sandy in the lower part. Locally, 25 to 30 feet of white vitreous quartzite or sandstone is present at the base.	75-100	650	650	
	— Unconformity — (Note 4)						
UPPER CAMBRIAN			Series of alternating dark smoky gray and light gray to light buff dolomite in zones 100-150 feet thick. Individual beds range from 1 to 10 feet thick.	600			No fossils found
			Buff-weathering sandy dolomite and greenish nodular shale. Sparingly fossiliferous.	50	1925-2280	2365-2870	*Elvinia* sp., cf. *Geragnostus tumidosus*, *Dellea* sp., *Pterocephalia* ?? sp.
MIDDLE CAMBRIAN	Bonanza King formation (Ref. 11)		Light creamy gray dolomite.	200-250			No fossils found
		Silver King dolomite	Very dark smoky gray to nearly black dolomite.	200-250			
			Dark smoky gray dolomite and partially dolomitized limestone, locally cherty and sandy. Intraformational pebble and cobble conglomerates occur. Individual beds 6 inches to 3 feet thick.	1525-1780			
	Cadiz formation (re-defined) (Ref. 11 and Note 3)		Buff and gray muddy limestone; purplish and reddish shale; greenish gray shale and platy quartzite.	540-690	440-590		(2) Fauna from upper 100-150 feet (Middle Cambrian) characterized by *Glossopleura*, *Clavaspidella*, *Zacanthoides* and *Alokistocare*. (Ref. 4, 11, 19)
LOWER CAMBRIAN					100+	1310-1380	(1) Fauna from 75-125 feet above the base (late Lower Cambrian) includes, *Nisusia* sp., *Hyolithes* sp., "*Agraulos*" sp., *Inglefieldia* cf. *I. affinis*, *Kochaspis* sp., *Kochiella* sp., *Proliostracus* cf., *P. noenygaardi*.
	Chambless limestone (Notes 1 and 2)		Massive weathering, light to dark gray limestone in beds 1 to 10 feet thick. Algal nodules throughout. Locally a 10 to 15-foot zone of platy, fossiliferous limestone occurs a little above the middle.	170-220			"*Girvanella*" sp., *Hyolithes* sp., *Paterina prospectensis*, *Olenellus bristolensis*, *Olenellus fremonti*. (Ref. 4, 5)
	Latham shale (Notes 1 and 2)		Fossiliferous greenish gray platy shale which weathers to platy and paper-thin fragments. Thin, buff-weathering sandy limestone layers are present.	55-75			*Paterina prospectensis*, *Olenellus bristolensis*, *Paedumias nevadensis*, *Paedumias clarki*. (Ref. 1, 4)
	Prospect Mountain quartzite (Note 1)		(6) Massive, brownish-weathering white quartzite in layers 2 to 6 feet thick.	120	1085 (max.)		No fossils found
			(5) Fine-grained, dark greenish gray, shaly to platy quartzite.	130			
			(4) Fine-grained, reddish-brown-weathering white quartzite in beds 6 inches to 2 feet thick. Locally the rock is a friable sandstone; cross-bedding and pebble-lenses are characteristic.	725			
			(3) Fine-grained, dark greenish gray platy quartzite.	50			
			(2) Light gray to reddish-brown-weathering limestone, locally dolomitized.	30-50			
			(1) Fine-grained, greenish-black, shaly quartzite. Local pebble lenses occur a few feet above the base.	10			
	—— Marked unconformity ——						
PRE-CAMBRIAN			Granite, gneiss, and schist				

References on pp. 34-35.

in the northern Providence Mountains.—Continued.

CONTAINED FOSSILS FOSSIL LOCALITIES (*See* Geologic Map)	SUGGESTED CORRELATION	ECONOMIC VALUE	UNCONFORMITIES
Locs. WHE 1, WHE 2	(1) Sultan limestone of the Goodsprings quadrangle and the upper 100-125 feet of the Goodsprings dolomite, Goodsprings quadrangle, Nevada (Ref. 12, 13). (1) Sultan limestone of the Nopah Range, California (Ref. 10)	Possibly mineralized along the East Providence fault between Bonanza King mine and Gilroy Canyon. Altered to marble east of Vulcan mine. Slightly mineralized in vicinity of Bonanza King mine.	
			Beds appear conformable. Magnitude of break established by regional relations. In the Nopah Range are several thousand feet of beds that do not occur in the section here described (Ref 8).
Locs. P-1098, P-1125, P-1127, P-2084, P-2136, P-1305	(Note 4)	Bonanza King mine is in this formation. Slightly mineralized along dikes on the range summit north of Silver King Canyon.	Possible unconformity (*See* Note 4)
	(1) Bonanza King formation, Nopah Range (Ref 8). (2) Major portion of "Goodsprings" dolomite, Goodsprings quadrangle (Ref. 12, 13).	(1) Mineralized along the East Providence fault north of Bonanza King mine. The Silver King mine is in this formation. Values in Au, Ag, Pb. (2) Mineralized and locally altered to marble at western end of Foshay Pass. Vulcan mine in this unit (Fe).	
Loc. P-271 Locs. P-432, P-432A	(1) Cadiz formation (re-defined) in the Marble Mountains, California (Note 3). (2) Cadiz formation of the Nopah Range, California; section (Units 5-A through 5-G) and the uppermost 80 feet of the Wood Canyon formation (Unit 4-D) of this section (Ref. 8).		
Loc. P-2400	(1) Lower Cambrian "algal limestone" of the Marble Mountains, California (Ref. 4). (2) "Algal limestone" member (4-N) of Wood Canyon formation, Nopah Range, California (Ref. 8). (3) "Combined Metals" bed, Pioche District, Nevada (Ref. 2, 25).	Mineralized in vicinity of Tough Nut mine (Au).	
Locs. P-9, P-11, P-5B, P-259	(1) Lower Cambrian shale of Marble Mountains, California (Ref. 4). (2) Member 4-M of Nopah Range, California, section (Ref. 8). (3) Shale between top of Prospect Mountain quartzite and base of "Combined Metals" bed, Pioche District, Nevada (Ref. 2, 25).		
	(1) Lower Cambrian quartzite of the Marble Mountains, California (Ref. 4). (2) Probably correlative with some part of Wood Canyon formation below the Zabriske quartzite member (4-H) in the Nopah Range. Lithologically quartzite has great similarity to the Stirling quartzite (Ref. 8). (3) "Tapeats" sandstone of Sheep Mountain, Jean, Nevada (Ref. 12, 13). (4) Prospect Mountain quartzite, Pioche District, Nevada (Ref. 25).	Mineralized in vicinity of Cornfield Spring. Tunnel was driven originally to explore a mineralized zone in lower part of quartzite. Principal value is iron as specular hematite.	
			Pre-Cambrian surface known to have a relief of the magnitude of 25 to 30 feet. It is noteworthy that very little coarse material is present in the basal beds of the quartzite.
		Mineralized at several places, both on northwest and east side of range. Principal value Au. Age of mineralization unknown; believed post-Paleozoic.	

(Table 1—Continued)

Note 1: In 1938 (Ref. 7) the names Tough Nut quartzite, Kelso shale, and Chambless limestone were proposed for the three lower formational units of Lower Cambrian age. The names "Toughnut" and "Kelso" are preoccupied, so that other formational terms are used herein.

Note 2: The Latham shale and Chambless limestone are both distinct and mappable lithologic units which the writer believes have widespread distribution in the southern Great Basin. The faunas are unquestionably Lower Cambrian, and the units appear to occupy an approximately constant stratigraphic interval. These units are correlated with members 4-N and 4-M of the Nopah Range section (Ref. 8), and with the "Combined Metals" bed and the green shale that separates it from the underlying Prospect Mountain quartzite as exposed on the west side of the Highland Range, Pioche District, Nevada (Ref. 2, p. 1156; and Ref. 25). There both units are distinct and mappable, and have the lithology, fauna, and stratigraphic position of their apparent counterparts in the Marble and Providence Mountains. The type locality of the Latham shale is designated as along measured section C_3-C_3' (See plate 2), about a mile southwest of Latham's cabin in the northern Providence Mountains. The Chambless limestone is named after Chambless Station on U. S. Highway 66 approximately 12 miles east of Amboy, California. The type locality is about 2 miles northeast of Chambless (Ref. 4 and 5) at an old quarry which is on the north side of a large wash and near its mouth. A trail is dimly visible from the wash to the quarry opening.

Note 3: As originally defined in the Marble Mountains (Ref. 11), the term "Cadiz formation" was applied to the Middle Cambrian portion of a quartzite, shale, and limestone sequence, the lower 100± feet of which was known to contain Lower Cambrian fossils (Ref. 3). The term was used in the Providence Range (Ref. 11), and was extended to the Nopah Mountains (Ref. 8) with the same faunal limitations for the base of the unit. This definition was criticized (Ref. 27) with some justice as establishing the base of the formation on a faunal basis. The writer here re-defines the Cadiz formation to include all beds between the top of the Lower Cambrian Chambless limestone and the base of the Middle Cambrian Bonanza King formation. The Cadiz is so delimited on the geologic map (plate 2). In both the Providence and Marble Mountains the formation as re-defined is a mappable lithologic unit. Compared with the Pioche section (Ref. 25), it occupies the combined stratigraphic position of the portion of the Pioche shale above the "Combined Metals" bed, the Lyndon limestone, and the Chisholm shale. Questions have been raised concerning the correlation of both the Lower and Middle Cambrian beds of the Nopah section with the Pioche section and the Providence-Marble Mountain section. Publications pertaining thereto are listed in the bibliography (Refs. 16, 27, 28, and 29).

Note 4: This 750±-foot unit was defined in 1936 (Ref. 11) as the Cornfield Springs formation. The upper 100± feet is now believed to belong with the overlying Devonian beds above a major unconformity. The basal 50-foot member of the formation is fossiliferous, and originally was assigned with little question to the Middle Cambrian on the basis of fossil identifications now known to be erroneous. The overlying dolomite section was tentatively included in the formation. In 1938 the name was extended to the Nopah Range (Ref. 8) on the basis of lithology and apparent fauna, although it was pointed out that, as there defined, the formation probably includes beds of Upper Cambrian age. Recent review of the faunas from the Providence Range and from the Cornfield Springs and Nopah formations of the Nopah Range by A. R. Palmer of the U. S. Geological Survey suggests that the Cornfield Springs at its type locality is of Upper Cambrian age. Additional faunal collections made recently by the writer and William H. Easton, and studied by Mr. Palmer, have confirmed this new age assignment. These findings raise several questions concerning formational terminology and correlation, both with the Nopah section and others. For this reason the name "Cornfield Springs formation" is not used here, and the two mappable members formerly assigned to it are designated simply as "Upper Cambrian" until work now in progress can clarify the relations in question.

Note 5: In the measured sections of the Bird Springs formation reported in 1946 (Ref. 23), the approximate position of the Pennsylvanian-Permian boundary was established on the basis of lithology and faunas. It is probable that this boundary can be mapped, but inasmuch as it was not, there is no basis for separation on the map of the Pennsylvanian and Permian portions of the unit here designated as the Bird Springs formation. In mapping, the base of the Bird Springs formation was drawn at the top of the distinctive Yellowpine member of the underlying Mississippian Monte Cristo formation. This follows Hewett's definition of the boundary in the Goodsprings quadrangle, Nevada (Ref. 13). In the Providence Mountains no definite basal sandstone or conglomerate was recognized, although beds low in the Bird Springs section contain sporadic rounded pebbles and grit of black chert. An unconformity is presumed to be present on the basis of regional considerations (Ref. 10, 18) and faunas.

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the portion of the mountains south of the pass. The latitude of Summit Springs has been chosen somewhat arbitrarily as the northern limit of the range. This boundary is not well defined physiographically, for the mountains merge gradually into the Mid Hills, a region of lower average altitude and relatively subdued relief. Summit Springs is immediately north of the northern limit of Paleozoic rocks; the Mid Hills are underlain by pre-Cambrian crystalline rocks and intrusive masses of younger granitic rocks.

The main divide of the range trends N. 20° E. For a distance of about 6 miles north of Foshay Pass the average altitude of the crest line is between 6,000 and 6,500 feet; farther northward the crest is about 1,000 feet lower. The highest point is Mt. Edgar, which is about 7,000 feet above sea level. The summit of Foshay Pass stands at approximately 4,375 feet, and Summit Springs is about 4,100 feet above sea level.

The longer, and in part steeper, slope is on the western side of the mountains facing Kelso Valley. Near Cornfield Springs, about 5 miles southeast of Kelso, the mountain front rises within a horizontal distance of about 2½ miles from an average altitude of 3,000 feet to the maximum of nearly 7,000 feet at Mt. Edgar. The eastern base of the range along Fenner Valley averages 4,500 feet above sea level, and the summit ridge lies from half a mile to 1½ miles to the west. In a general way, the eastern side of the range is a very large-scale dip slope.

The most striking physiographic feature of the mountains is the series of great west-facing, nearly vertical cliffs that lie immediately west of the main divide. These cliffs, supported by massive Mississippian limestone, are most imposing when viewed from points near Kelso. The western base of the mountains is lobate in outline, and wide, alluvium-floored washes head into the range from Kelso Valley. These are separated by sharp ridges that rise eastward in a buttress-like manner to meet the base of the great cliffs. The most prominent of these ridges borders Cornfield Springs Canyon on the south. It is 1¾ miles in average width, and its summit reaches an altitude of about 4,000 feet.

In marked contrast with the western side, the eastern face of the range is very straight, and in part has the character of an obsequent fault-line scarp. The canyons draining into Fenner Valley are deeply cut, and some have near-vertical walls. To only a minor degree are they floored with alluvial deposits. Opposite the northern part of the range Fenner Valley rapidly narrows toward the north. In the vicinity of Summit Springs, Wild Horse Mesa, a high-standing area developed on a thick series of flat-lying Tertiary volcanic rocks, extends westward almost to the eastern border of the range.

THE GEOLOGIC SECTION

Stratigraphy. The stratigraphic section in the northern Providence Mountains includes 13 formational units that lie above the pre-Cambrian rocks. These range in age from Lower Cambrian to Quaternary, and have a maximum aggregate thickness of 12,215± feet. Nine formations are of Paleozoic age, one is Mesozoic, one is Tertiary, and two are Quaternary. Lithologic, paleontologic, and stratigraphic data pertaining to these units are summarized in table 1.

Igneous Rocks. No attempt was made in the field to subdivide the pre-Cambrian igneous and metamorphic complex. Three intrusive rocks of post-lower Triassic age are recognized. These cannot be dated exactly, but they are discussed below in what is believed to be their order of decreasing age.

Biotite-hornblende-augite syenite crops out northeast of the Bonanza King mine, but it is best exposed along Foshay Pass, where it is both intrusive into, and in fault contact with, various units of the Paleozoic sequence (plate 2). Lamey (1948) described the rock as a coarsely granitoid to slightly porphyritic monzonite, mottled with pink and lilac orthoclase, white plagioclase, and black biotite. In thin section, secondary alteration is seen to be extensive, with the development of epidote, zoisite, sericite, and chlorite; some of the quartz also may be of secondary development. The iron ore at the Vulcan mine is a contact-metamorphic deposit believed to be related in origin to the syenite.

On the northern slope of the ridge that borders Cornfield Springs Canyon on the north, dark olive green sills of hornblende-bearing lamprophyre intrude Lower and Middle Cambrian rocks, and in turn have been cut by rhyolite dikes that follow post-lamprophyre faults. The age relation of the lamprophyre to the rhyolite is clearly established, but its relation to the syenite is uncertain because nowhere are these two rocks in exposed contact.

Biotite rhyolite, designated on the geologic map (plate 2) as the Fountain Peak rhyolite, forms the main intrusive mass centering around Fountain Peak, as well as the dike system that extends therefrom. The Fountain Peak igneous mass is composite in character. As mapped, it includes at least two intrusive facies differing slightly in color and texture, as well as an unknown amount of pyroclastic material having the general composition of a rhyolite vitric tuff. As alteration of both the intrusive and pyroclastic rocks has been considerable, exact compositions are uncertain.

As a whole the Fountain Peak rhyolite weathers to a dark reddish brown. It forms prominent craggy slopes which in color and form contrast sharply with the adjoining areas underlain by limestone. At the few places where they are visible, the contacts of the intrusive rocks are sharp. On the west slope of the range, above the Vulcan mine, the rhyolite-limestone contact dips beneath the intrusive mass. The prominent dike system that extends northward from Fountain Peak into the limestone suggests that in this area a large body of intrusive rhyolite may be present at relatively shallow depth. This dike system is not shown in the structure sections (plate 3). Alteration of the limestone by the rhyolite has been slight. At some places the limestone has been bleached, at others some dolomitization has occurred, and at still others the limstone is rusty-brown in color, possibly owing to the addition of iron.

The age relation between the Fountain Peak rhyolite and the volcanic rocks present in Fenner Valley and on Wild Horse Mesa has not been firmly established. On the northwest side of Fountain Peak the rhyolite is intrusive into a series of bedded tuffs, agglomerates, and water-laid volcanic sediments that contain some rounded cobbles of limestone. These rocks rest unconformably on Lower Triassic limestone. Superficially, at least, these bedded tuffs and agglomerates resemble units in the volcanic series of Wild Horse Mesa. It is possible that the Fountain Peak rhyolite mass is the filling of a volcanic conduit whence came the tuffs, agglomerates, and flows that form the Wild Horse Mesa section, as well as those on the northwest slope of Fountain Peak. In the latter area, it is presumed that material ejected early in the volcanic cycle was later intruded by other igneous material.

The rhyolite dike system, which is clearly related to the Fountain Peak intrusive, was emplaced after the major episode of faulting. Dikes do not cross the East Providence fault, nor do any of them appear to have been intrusive along it. As far as could be determined, there is no evidence that the rhyolite dike system was faulted after its emplacement, although some minor faulting postdates the volcanic series in Fenner Valley and on Wild Horse Mesa. As noted above, the rhyolite cuts the lamprophyre dikes, and it also is intrusive into the syenite along Foshay Pass.

STRUCTURE

The northern Providence Mountains constitute an easterly tilted block within which faulting is the dominant structural feature. Folding is very minor, and in all occurrences appears to be related in origin to the faulting. The fault pattern, the direction and amount of dip, and the direction and amount of displacement of individual faults are shown in plate 4. The writer found no evidence of major low-angle overthrusts such as have been reported by Hewett (1931) in the Goodsprings region. Faulting occurred during at least three and possibly five periods. In order of decreasing age, these are: (1) *High-angle reverse faults.* The East Providence fault and reverse faults within the range and along parts of its western border belong in this group. In general these are faults of rather large displacement. (2) *High-angle normal faults.* Most of the relatively minor faults within the range belong in this category. (3) *Low-angle normal faults.* Faults of large displacement that cross the ridge south of Cornfield Springs Canyon, and some faults of minor displacement south of Latham's are the most prominent of this group. (4) *High-angle reverse and normal faults locally present along the western front of the range.* It is uncertain whether these belong in one of the groups listed above or are younger (plate 3, sections B-B′ and C-C′). (5) *High-angle normal faults that cut the Miocene (?) volcanic rocks in Fenner Valley and on Wild Horse Mesa.* The age relation of these to the faults of group (4) is not known.

The East Providence fault forms the eastern structural border of the range, and has controlled the eastern topographic border. The easterly dip of the fault plane can be seen not only in outcrop but also in the mine workings of the Bonanza King and Silver King mines. Though structurally high, the area east of the fault is now topographically low. This same topographic relation existed in pre-Miocene (?) time, as is indicated by the relation of the volcanic section on Wild Horse Mesa to the eastern front of the present mountains. Thus the Providence Mountain block is at least pre-Miocene (?) in age, and is not a feature produced by relatively recent faulting (Emery and Easton, 1951). The major part of the faulting within the range is of about the same age, although minor post-volcanic faulting occurred in Fenner Valley. The obvious correspondence between the fault pattern of the range and the rhyolite dike system (plate 4) indicates that the major part of the fault pattern was developed prior to intrusion of the Fountain Peak rhyolite. There is no evidence of recent fault movement along the margins of the range.

The low-angle normal faults are the outstanding structural features in the range. Those south of Cornfield Springs Canyon are best exposed and also have the maximum known displacement, which locally is as much as 4,500 feet stratigraphically. The origin of this type of fault is puzzling, and the writer offers no solution to the problem. Similar faults have been reported by Longwell (1945) in the area north of Las Vegas, Nevada, where presumably they are related to very large-scale anticlinal folds. Two other possible explanations can be mentioned: (a) The low-angle faults were originally high-angle, west-dipping normal faults that have been rotated to a gently inclined position by later eastward tilting of the range. This explanation is not tenable, in view of the other fault features of the mountains. (b) The low-angle faults were caused by landsliding on a large scale. This seemingly would necessitate marked oversteepening of the western range front and movement of the landslide blocks under essentially surface conditions. This is not an impossible explanation, but the rock masses above and between the low-angle faults do not show the brecciation and rotation that might be reasonably expected under such conditions.

MINERALIZATION

At least two periods of mineralization are recognizd within the northern Providence Mountains. The earlier of these is related to the syenite, and the Vulcan iron deposits are believed to be its major representatives. The mass of intrusive rock locally altered the Paleozoic limestone to marble, and both rocks were later cut by major faults such as the East Providence fault and the fault along Foshay Pass.

Underground studies in the Bonanza King mine suggest that ore deposition there was controlled in part by faults closely related to the East Providence fault, and that mineralization followed the major part of the faulting. It is believed that this period of mineralization reasonably can be related to the Miocene (?) volcanism.

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5. THE SAN ANDREAS FAULT ZONE FROM SOLEDAD PASS TO CAJON PASS, CALIFORNIA[*]

By Levi F. Noble[†]

INTRODUCTION

The San Andreas fault, one of the dominant geologic features of southern California, defines a zone of rupture that extends more than 600 miles across the State from the coastal area north of San Francisco to the area south of the Salton Sea (fig. 1). This zone, the San Andreas fault zone or "San Andreas rift," is half a mile to a mile wide in most places. It has a curiously direct course across mountains and plains, with little regard for gross topographic features, and yet it influences profoundly the local topographic and geologic features within it.

The San Andreas fault is a part, perhaps a dominant part, of the great fault system of California, which has broken the rocks of the State into a mosaic of blocks. Some faults of the system branch from the San Andreas and may be closely related to it; others appear to have been cut off or displaced by the San Andreas, and their genetic relations to this master break are not at all clear. Still other faults are essentially parallel to the San Andreas, a few of them for distances of many miles. The San Jacinto fault, for example, lies parallel to and a few miles south of the San Andreas fault in much of the area described in this paper, but it diverges widely beyond this area to the southeast.

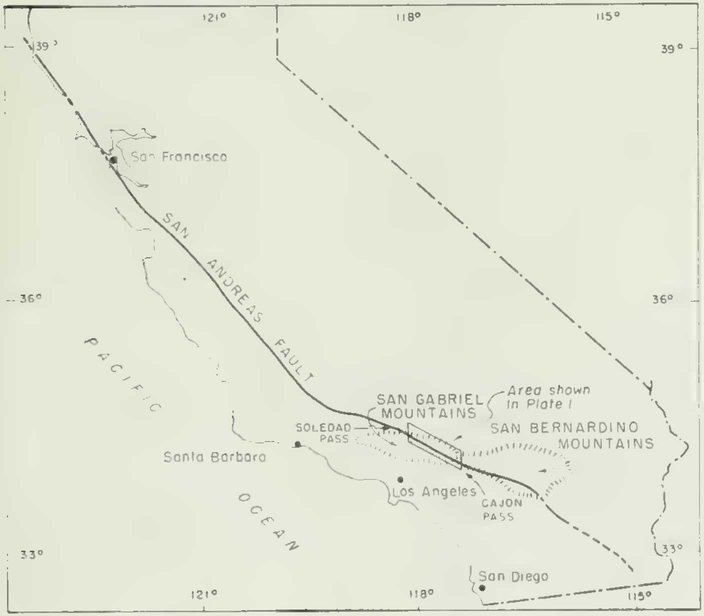

Figure 1. Sketch map showing course of San Andreas fault.

Although the area discussed in this paper was visited and the rock formations were accurately described by Blake (1856) as early as 1853, the San Andreas fault and its surface features were not recognized by a geologist until more than 40 years later, when Schuyler (1896-97, pp. 711-713) briefly described features of the "great earthquake crack" that had been formed by the Fort Tejon earthquake of 1857. These features were subsequently described in more detail by Fairbanks for the California Earthquake Investigation Commission (Lawson, et al., 1908, pp. 43-45). Simpson (1935) reported on the general character of the rocks and structural features of the Elizabeth Lake 30-minute quadrangle, which includes the western part of the area treated herein, and Wallace (1949) described in greater detail the features along a 19-mile strip of the fault zone just west of the area.

The writer has carried on a study of the 50-mile segment of the San Andreas fault zone between Soledad and Cajon Passes intermittently since 1910. Preliminary results of this work were briefly recorded more than 20 years ago (Noble, 1926, 1932, 1933); detailed descriptions of two areas along the fault zone have been published recently (Noble, 1953, 1954); and a fuller report on the structure and geology of this segment of the fault zone is in preparation.

Many geologists—among them H. E. Gregory, Charles Schuchert, W. M. Davis, Bailey Willis, A. C. Lawson, J. P. Buwalda, F. L. Ransome, W. C. Mendenhall, George and Anna Stose, P. B. King, and H. G. Ferguson—visited the writer during the course of his investigations and contributed valuable discussion and suggestions. The writer also is indebted to C. L. Gazin, who assisted with the field work in 1932, and to E. S. Larsen, Jr., and Charles Milton, who studied thin sections of various crystalline rocks from the fault zone and adjacent areas.

GEOLOGIC RELATIONS

General Features. The San Andreas fault extends in an east-southeasterly direction from points near the Palmdale area toward

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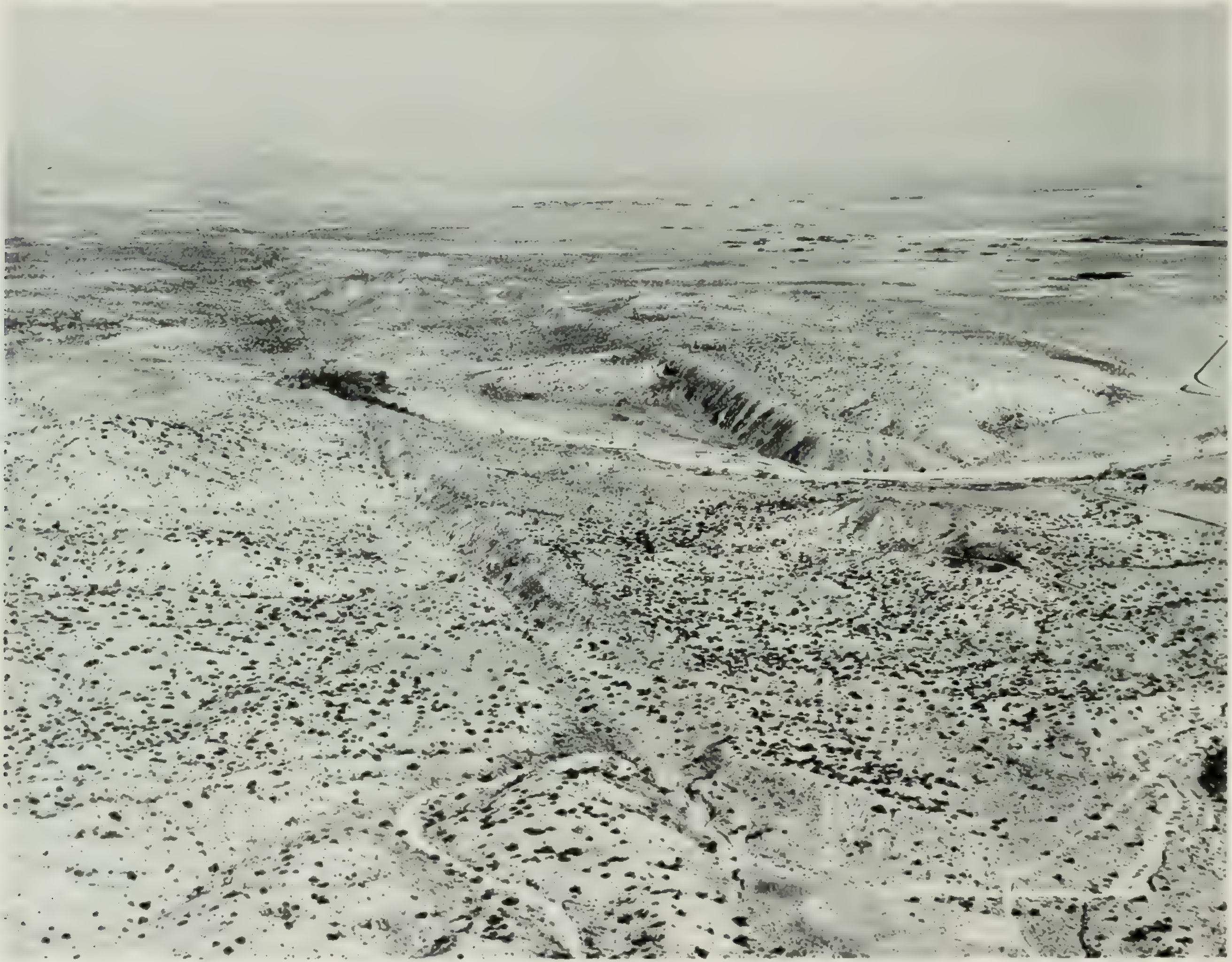

FIGURE 2. San Andreas fault zone; view northwest toward Palmdale (middle distance). Trench of San Andreas fault is at left, and scarp of Little Rock fault is at right. Exposed in the block between these parallel faults are sedimentary rocks of Pliocene and Pleistocene age; the blocks that flank the fault zone are mainly granitic rocks, with some in-faulted slices of Tertiary sedimentary rocks. Note the concentration of vegetation in Little Rock Wash where it is crossed by the San Andreas fault. *Photo by J. S. Shelton and R. C. Frampton.*

Cajon Pass, and in a general way separates the San Gabriel Mountains on the southwest from the western part of the Mojave Desert region on the northeast. Throughout this segment, the fault is marked by a straight and almost continuously traceable chain of scarps, ridges, and troughlike depressions, most of which involve Quaternary alluvial deposits and hence afford clear testimony to many earth movements earlier than those of historic record, yet geologically recent. In the western part of the area the San Andreas fault forms a trench and ridge that cut across the spurs and lines of northward drainage from the San Gabriel Mountains (fig. 2), and farther east its course is marked by Swartout Valley and Lone Pine Canyon (fig. 3).

A second major fault, the San Jacinto, is essentially parallel to the San Andreas from Cajon Creek to a point near Little Rock Creek where it curves northward and merges into the San Andreas fault zone. These two master breaks are 2 to 4 miles apart in most places, and together they define an elongate tectonic belt of extreme structural complexity (plate 5). Flanking this belt are major blocks that consist mainly of crystalline basement rocks in which the structure is less complex.

As shown in plate 5, many other faults lie on each side of the San Andreas fault. Some of these are secondary only in magnitude to the San Andreas and like it show evidence of recent movements in the Quaternary deposits and large displacements in the older rocks. Unlike the San Andreas, however, they do not constitute major lines of discontinuity between markedly dissimilar formations. Most are not continuously straight but instead are arranged en echelon or are characterized by numerous subparallel branches. Many of the individual breaks are separated by zones of intense crushing in the pre-Quaternary rocks.

Although most of these faults are parallel to the San Andreas and San Jacinto faults, or diverge from them at low angles, a few major breaks diverge abruptly and have an almost due westerly trend; some of these faults may well be cut off or offset by the San Andreas and San Jacinto faults. Typical examples are the Soledad fault, which extends westward into the Soledad basin (see Bailey and Jahns, Contribution No. 6, Chapter II) from a point near Little Rock Creek; the Fenner fault, which trends westward across Pinyon Ridge; the Cleghorn fault, which extends eastward into the San Bernardino Mountains from Cajon Creek; and the San Gabriel fault zone, which extends westward into the San Gabriel Mountains from Lytle Creek (plate 5).

The rocks of the San Andreas fault zone and the adjacent major blocks can be grouped into four types: (1) the Pelona schist and associated rocks, a metamorphosed sedimentary and volcanic sequence of probable pre-Cambrian age; (2) widespread plutonic rocks, for the most part of Mesozoic age, that generally range in composition from quartz diorite to granite; (3) several Tertiary formations, including volcanic rocks and both marine and nonmarine sedimentary rocks, mostly confined in their extent to the fault zone; and (4) Quaternary alluvial-fan, stream, and playa deposits. In the eastern half of the area mapped, all Tertiary rocks lie north of the San Andreas fault; in the western half of the area, they lie south of the fault or within the fault zone. The pre-Tertiary rocks are different on opposite sides of the San Andreas fault. All these rocks are noted in the following discussions of the fault zone, but for an integrated presentation of their distribution, nature, and sequence the reader is referred to the legend in plate 5.

Area North of San Andreas Fault. The structural block north of the San Andreas fault is underlain by a batholith of granitic rocks and the injected rocks of its contact zone. The injected rocks contain a large amount of limestone, metamorphosed to marble. The batholith is of wide extent in the western Mojave Desert region. In Holcomb Ridge it encloses elongate, steeply dipping roof pendants of marble oriented parallel with the San Andreas fault. In the Table Mountain ridge the injected rocks include marble, dioritic gneisses, mica schist, and migmatite, all intricately intruded by the granitic rocks.

The granitic rocks are Mesozoic, perhaps Cretaceous, in age (Woodford, 1939, p. 257), and the included limestone probably is late Paleozoic in age (Noble, 1932, p. 356). Farther east, in the San Bernardino Mountains, the crystalline rocks were not studied, but they include large bodies of granitic plutonic rocks, schist, gneiss, crystalline limestone, and several kinds of hybrid rocks.

In the drainage area of upper Cajon Creek are many spectacular exposures of upper Miocene conglomeratic sandstone forming bold upturned ledges. Interbedded with the sandstone are siltstone, gypsiferous shale, and a few limestone beds. These strata, which have long been known locally as the ''Cajon beds,'' are at least in part correlative with the Punchbowl formation farther west and on the opposite side of the San Andreas fault. The section is more than 8,000 feet thick and has been dated by means of vertebrate fossils (C. L. Gazin and Chester Stock, personal communications). It lies upon the granitic basement rocks at a few places; elsewhere it is faulted against them (plate 5). At one place it lies upon the Vaqueros formation and at another upon the Martinez formation; these unconformable contacts are too small to show upon the map.

Four small patches of fossiliferous basal beds of the marine Vaqueros formation of early Miocene age lie upon a high hill of

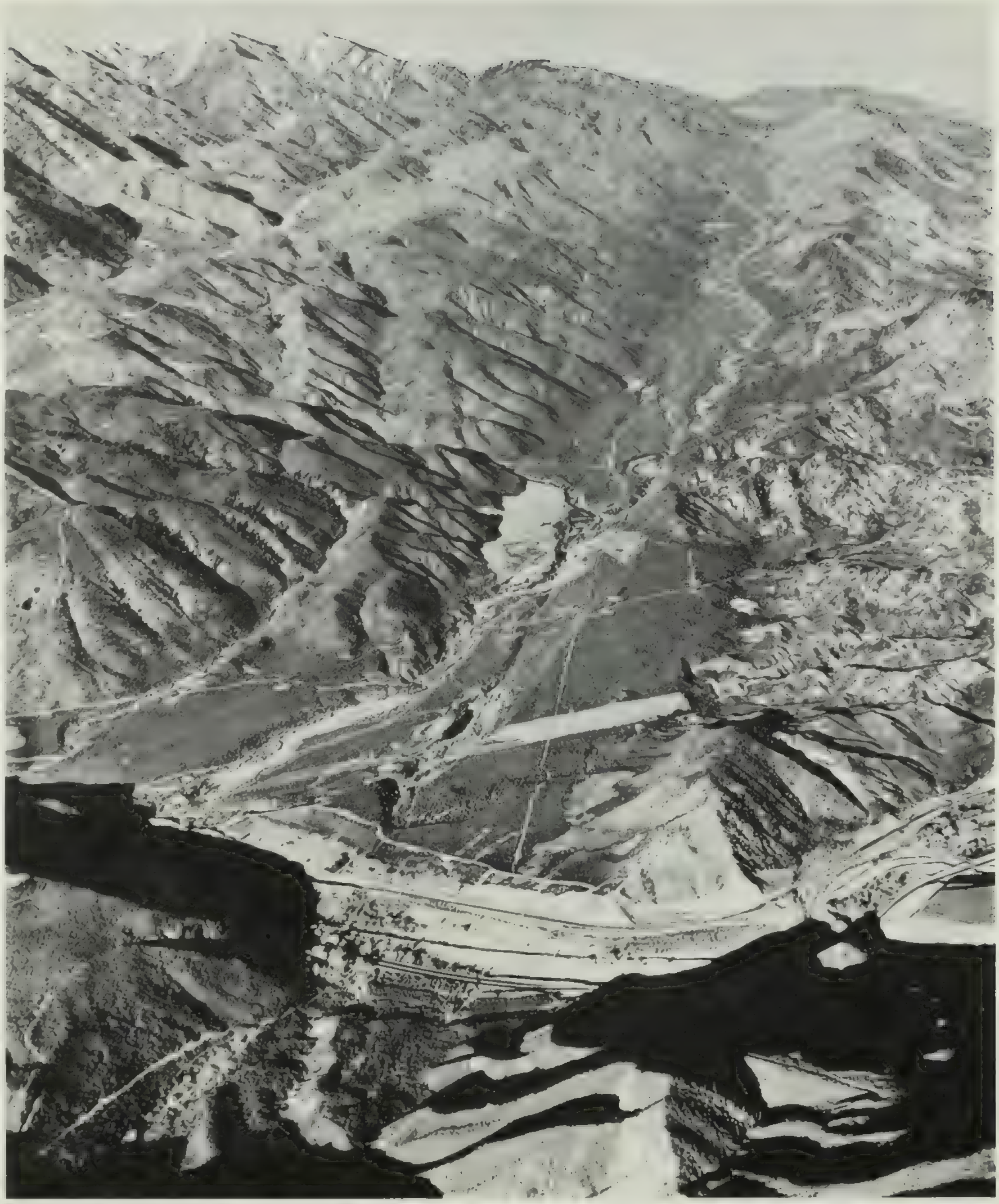

FIGURE 3. San Andreas fault zone; view west-northwest from Cajon Canyon into the San Gabriel Mountains. The main fault extends up Lone Pine Canyon. Near the mouth of the canyon are a sag pond and a small stream offset caused by shifts along the fault. The nearly parallel San Jacinto fault extends up Lytle Canyon in left distance. San Antonio Peak is at the upper left corner of the view. *Photo by R. C. Frampton and J. S. Shelton.*

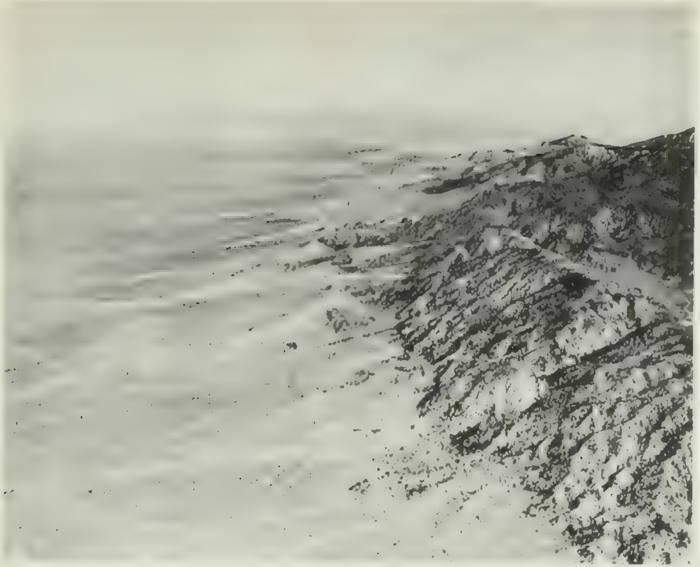

Figure 4. Hogbacks (Inface Bluffs) of Quaternary gravel, sand, and silt (Shoemaker gravel) derived from the San Gabriel Mountains; view east toward San Bernardino Mountains. Beds of the Pleistocene Harold formation underlie the low area between the hogbacks and the north slopes of the Table Mountain ridge at right. Mescal Wash in middle distance. *Photo by J. S. Shelton and R. C. Frampton.*

granodiorite that rises north of the San Andreas fault at Lone Pine Canyon; the hill is a wedge of basement rock pushed up through strata of the Punchbowl formation (plate 5). The fossils have been described by Woodring (1942, pp. 78-83). The relation of these beds to other outcrops of the Vaqueros formation in California has remained a puzzle since their discovery in 1929, for the nearest rocks of the Vaqueros north of the San Andreas fault lie in the San Joaquin Valley, 90 miles northwest of Cajon Creek, and the nearest strata of the Vaqueros formation south of the fault lie in the Santa Ana Mountains, 40 miles to the southwest. However, a small block of unfossiliferous beds that are lithologically like the Vaqueros in the Cajon area is faulted into granodiorite south of the San Andreas fault 2 miles west of the Valyermo quadrangle. These beds are correlated tentatively with the Vaqueros formation by the writer (plate 5).

Two disconnected outcrops of basal beds correlated with the marine Martinez formation of Paleocene age lie near Cajon Creek just north of the San Andreas fault (plate 5); the steeply dipping beds in one of these outcrops are well exposed in cross-section in a road cut on U. S. Highway 66. The beds in both outcrops lie unconformably upon granodiorite, are folded and intricately faulted, and are overlapped at one place by the Punchbowl formation. A thin wedge of crushed basement rock and sandstone of the Punchbowl (concealed beneath alluvium) separates the blocks of Martinez from the San Andreas fault. No other Martinez strata crop out north of the San Andreas fault nearer than the San Joaquin Valley.

In an earlier paper of the writer (Noble, 1933, pp. 12, 17) the outcrops of the Martinez formation just described were incorrectly stated to be Vaqueros and were incorrectly labeled Miocene in the legend of the accompanying map (Noble, 1933, plate 3); however, they are correctly labeled on an airplane view (Noble, 1933, plate 4B) accompanying the paper.

As traced northward down a gently sloping pediment toward the floor of Antelope Valley, the granitic rocks of Holcomb Ridge are overlain by gravel, sand, and silt of the Harold formation of Pleistocene age. The pediment is an exhumed feature that represents a surface of erosion formed at the beginning of the time of deposition of the Harold formation. This erosion surface is widespread in the area mapped but has been dislocated at many places by faulting and warping. The north slope and the crest of the San Bernardino Mountains at Cajon Pass are parts of it, as are the even crests of the ridges (fig. 3) in the San Andreas-San Jacinto tectonic belt. It is spectacularly exposed in the Punchbowl trough at the Devil's Punchbowl (fig. 7). The surface represents an angular unconformity at the base of the Harold formation that bevels all Tertiary and pre-Tertiary rock formations and all the complex structure in the San Andreas fault zone.

The Harold formation is 1,200 feet thick at Cajon Pass but thins westward and is only 200 feet thick in the west half of the area mapped. Everywhere the lower part of the formation is finer grained than the upper part, suggesting that the San Gabriel Mountain arch did not begin to rise until after the lower part of the Harold had been laid down.

The Pleistocene age of the formation is established by fossils found by C. L. Gazin in the Pearland quadrangle (Noble, 1953). In the Cajon Creek area, several beds in the basal part of the Harold section contain scattered vertebrate remains that, according to Gazin (1932, personal communication), are upper Miocene of the stage indicated by fossils in the underlying Punchbowl formation nearby. On the basis of this evidence, the writer erroneously assigned the Harold formation of the Cajon Creek area to the upper Miocene in two former papers (Noble, 1932, p. 356; 1933, p. 13). Subsequent

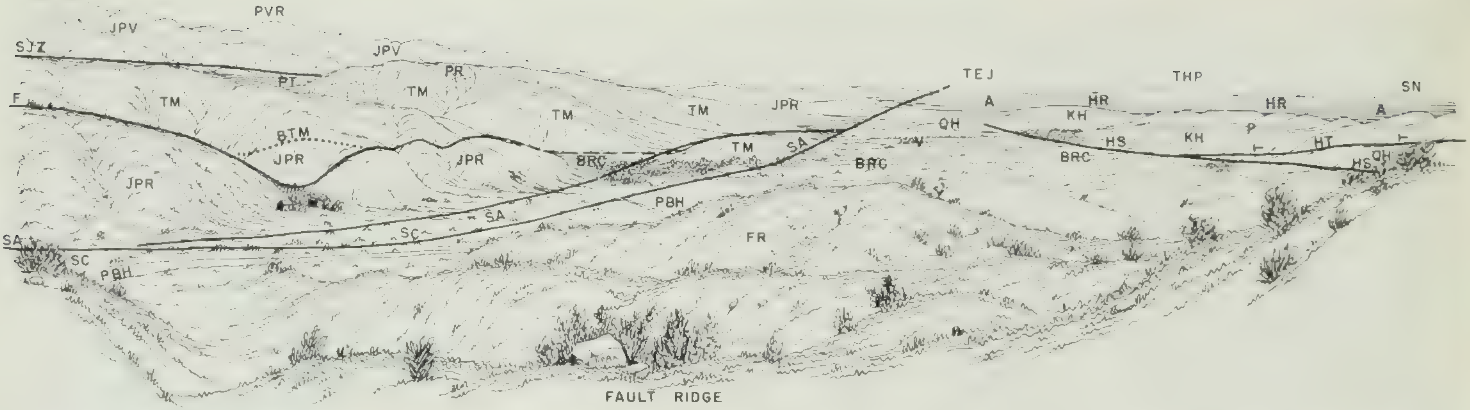

FIGURE 5. San Andreas fault zone; view west across Valyermo Ranch. At right are Holcomb Ridge (HR) and exhumed pediment (P), with Antelope Valley (A), Tehachapi Mountains (THP), and Sierra Nevada (SN) beyond. The Holcomb thrust fault (HT) and Hidden Springs fault (HS) bound the San Andreas fault zone on the north. Beyond and to the left of the fault ridge (FR) in foreground is the San Andreas fault (SA), which defines Shoemaker Canyon (SC), crosses Big Rock Creek (BRC), and extends west-northwestward toward Tejon Pass (TEJ). In the distance at left are Pinyon Ridge (PR), the Punchbowl trough (PT), the San Jacinto fault zone (SJZ), and Pleasant View Ridge in the San Gabriel Mountains (PVR).

Major rock types, from left to right, include Pleasant View complex (JPV) of the San Gabriel Mountains, Martinez formation (TM) with its unconformable contact (BTM) on the Pinyon Ridge granodiorite (JPR), Harold formation (QH), and Holcomb quartz monzonite (KH).

Valyermo Post Office (V) and Pearblossom Highway (PBH) lie in trough of San Andreas fault zone. *Sketch by Philip B. King.*

examination of the locality has led to the conclusion that the remains are detrital material eroded from the underlying Punchbowl beds, and the Harold formation has since been assigned to the Pleistocene.

The Harold formation at Cajon Pass is overlain by 200 feet to as much as 900 feet of gravel, sand, and silt derived from the San Gabriel Mountains to the south. These younger deposits are now exposed in a series of hogbacks that extend eastward for many miles along the base of the Table Mountain ridge (fig. 4) to Cajon Pass, where they form infacing bluffs and have been known as the "inface gravels." They are now termed the Shoemaker gravel (Noble, 1954). They are everywhere overlain by alluvial-fan and stream deposits washed from the San Gabriel Mountains (Noble, 1933, pp. 17, 19) before the valley of Cajon Creek was excavated.

Area South of San Andreas Fault. South of the San Andreas fault pre-Tertiary basement rocks form the San Gabriel Mountains, which stand at altitudes of 4,000 to 10,000 feet in the area under discussion. In the western part of the area, the block between the San Andreas and San Jacinto faults comprises many smaller fault-bounded blocks, some of which consist in part of Tertiary sedimentary rocks. Farther east, in contrast, the block between the two main faults consists wholly of basement rocks, and forms part of the high ground of the San Gabriel Mountains (plate 5).

The oldest of the crystalline rocks is the Pelona schist, a thick sequence of quartz-mica schist, feldspathic quartz-mica schist, chlorite-rich schist, actinolite-mica schist, and minor amounts of quartzite, crystalline limestone, and amphibolite. It probably is pre-Cambrian in age. Younger members of the basement complex include anorthosite and associated gabbroic rocks, hornblende-rich diorite, plutonic rocks of quartz dioritic to granitic composition, numerous hybrid schists and gneisses, and dike rocks among which amphibolite, pegmatite, and aplite are widely represented. Some of these rocks, including the anorthosite, may well be as old as pre-Cambrian, but most of the plutonic types probably are Jurassic or Cretaceous in age (Miller, 1934, pp. 61-65; Simpson, 1935, p. 384; Woodford, 1939).

The Pelona schist borders the San Andreas fault throughout the eastern half of the area mapped, where it underlies Blue Ridge, Pine Mountain, and the ridge between Lone Pine Canyon and Lytle Creek. It does not crop out in the western half of the area. Younger plutonic rocks are in fault contact with the schist in many places, especially in the San Andreas-San Jacinto tectonic belt, and in some places they are intrusive into the schist. They are separated from the schist in the highest part of the San Gabriel Mountains by the widespread Vincent thrust fault, which is spectacularly ex-

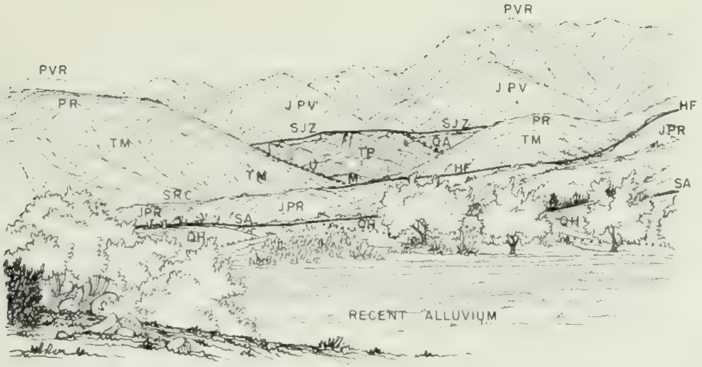

Figure 6. Pinyon Ridge (PR) and San Gabriel Mountains; view south up Sandrock Canyon (SRC) from Valyermo Ranch. Beds of the Harold formation (QH) form the ridge (Earthquake Hill) on the near side of the San Andreas fault (SA), immediately beyond which is a higher ridge of granodiorite (JPR). The Martinez formation (TM) underlies the part of Pinyon Ridge here shown, and visible through the gap in this ridge are the gently dipping beds of the Punchbowl formation (TP) on the north limb of the Punchbowl syncline. Quaternary older alluvium (QA) overlies the Punchbowl formation, which in turn rests unconformably upon the Martinez formation. A red megabreccia (M) of Martinez blocks lies immediately above this unconformity (U). Beyond the Punchbowl trough are the San Jacinto fault zone (SJZ) and the crystalline rocks (JPV) of Pleasant View Ridge (PVR). *Sketch by Philip B. King.*

posed on the bold faces of Mount Baden-Powell and San Antonio Peak (plate 5 and fig. 8). This fault commonly dips southwestward at angles less than 45°, but locally it is folded or warped. It is marked at many places by considerable thicknesses of mylonite. It cannot be younger than Mesozoic in age, as it is cut by the youngest intrusive rocks of the late Mesozoic igneous complex.

At the western edge of the mapped area are scattered exposures of the Vasquez formation, a thick sequence of coarse-grained continental strata with associated andesite and basalt. The sedimentary rocks probably are Oligocene in age, but may extend into the earliest Miocene. They are unconformably overlain by fossiliferous lower Miocene beds in areas farther west (Jahns, 1940, p. 170). The Vasquez formation in this area is preserved as erosional remnants in downfaulted blocks and in general is separated from the crystalline rocks of the San Gabriel Mountains by the Soledad fault.

San Andreas Fault Zone. In the western half of the area mapped, the San Andreas fault zone is a wide depression whose floor consists for the most part of broad alluvial surfaces diversified by low ridges that parallel the depression (figs. 2, 5). In the eastern half of the area nearly all alluvium occupies a narrow trough that encloses the San Andreas fault, and most of the surface of the zone is bedrock (fig. 3). The fault zone, which is structurally a depressed area, contains numerous fault-bounded masses of Tertiary and pre-Tertiary rocks. These masses, as well as others that flank the zone, represent slices and lenses that have been raised or depressed with respect to adjacent blocks by movements within the zone. Some of the ridges are sharp anticlines in Quaternary deposits.

Perhaps the most striking features in the fault zone are numerous large wedges of granitic basement rock that have been pushed up through the Punchbowl formation of upper Miocene age near Little Rock Creek south of the San Andreas fault and near Cajon Creek north of the fault. Some of the faults that border the wedges dip steeply beneath them, suggesting that the wedges taper downward as well as laterally and have been dragged along or squeezed up.

A wedge of crushed granitic basement rock, commonly concealed beneath Quaternary deposits and at many places so intricately fractured that it resembles fault gouge, borders the San Andreas fault throughout the area mapped. Thin slivers of extremely disordered upper Miocene strata of the Punchbowl formation border the wedge and at places are intricately involved in it by faulting. This belt of crushed rocks is believed to mark the break along which large strike-slip movements took place in pre-Quaternary time.

A particularly interesting feature of the major block between the San Andreas and San Jacinto faults is the Punchbowl trough south and southwest of Valyermo. In this structurally depressed area is more than 6,000 feet of marine shale, arkosic sandstone, and conglomerate of the Martinez formation, of Paleocene age (Dickerson, 1914). This formation comprises two members that are everywhere in fault contact. The lower member and underlying granodiorite have been thrust over the upper member along the Pinyon fault.

Both the Martinez formation and the Pinyon thrust fault were folded and eroded prior to deposition of the overlying Punchbowl formation of late Miocene age, which consists of nonmarine conglomerate, sandstone, siltstone, and gypsiferous shale. This section contains scanty vertebrate remains that appear to be related to the Barstow fauna of the Mojave Desert region (Chester Stock, personal communication; see also Savage and Downs, Contribution No. 6, Chapter III) and probably is in part correlative with the Mint Canyon formation of the Ventura basin to the west (Jahns, 1940, pp. 171-172). The Punchbowl strata have been folded into a broad syncline and are well exposed in a spectacular basinlike area known as the Devil's Punchbowl (fig. 6). The Punchbowl and San Jacinto faults bound this area on the south, and on its north side is the easily recognized unconformity between the Martinez and Punchbowl for-

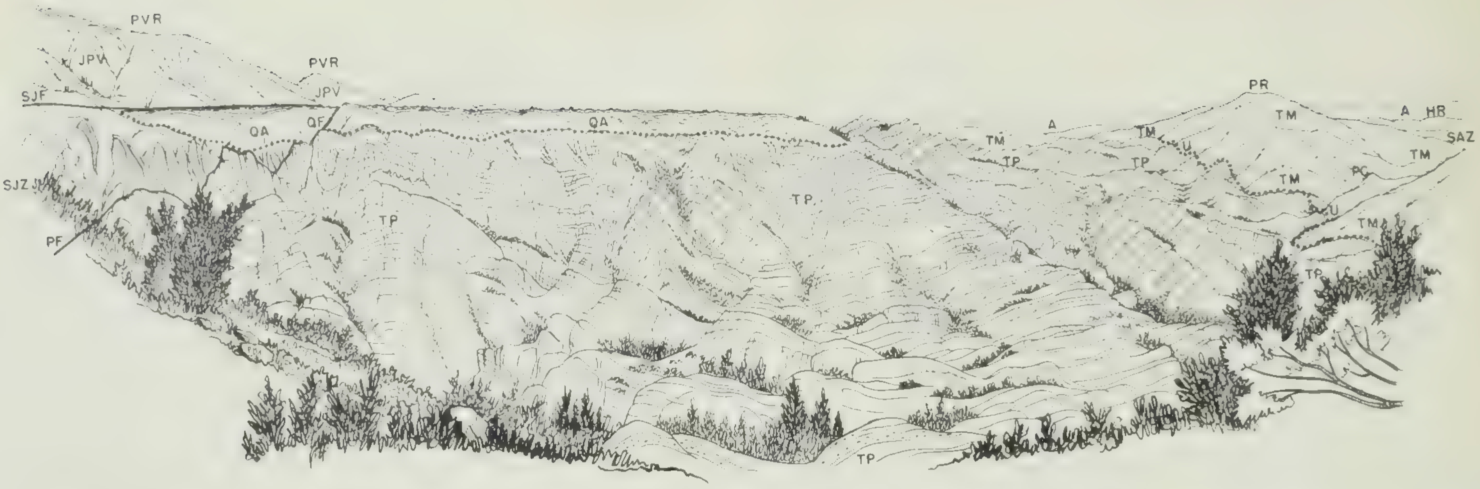

FIGURE 7. The Devil's Punchbowl; view northwest along axis of Punchbowl syncline from Devil's Punchbowl trail. From left to right, sketch shows Pleasant View Ridge (PVR), the San Jacinto fault (SJF), the crush zone (SJZ) between the San Jacinto fault and the Punchbowl reverse fault (PF), beds of the Punchbowl formation (TP), the canyon of Punchbowl Creek (PC) through Pinyon Ridge (PR), the San Andreas fault zone (SAZ), and Holcomb Ridge (HR). Antelope Valley is in the far distance. The crystalline rocks of the San Gabriel Mountains (JPV) are separated from the Punchbowl strata by a crush zone in which white aplite and dark metadiorite are prominent. Quaternary older alluvium (QA) lies on an erosion surface that bevels the Punchbowl formation, and a Quaternary fault (QF) cuts this alluvium on line of the Punchbowl fault. The unconformity (U) between the Punchbowl formation and the underlying Martinez formation (TM) is clearly shown along the base of Pinyon Ridge. *Sketch by Philip B. King.*

mations (fig. 7). The Punchbowl beds were laid down in a northwest-trending structural trough coinciding with and at places overlapping the San Andreas-San Jacinto tectonic belt. The trough has been intermittently under intense compression since before the deposition of the Punchbowl strata, with attendant episodes of faulting and synclinal folding.

LATERAL DISPLACEMENT ALONG THE SAN ANDREAS FAULT

In the following description the writer offers quantitative evidence for pre-upper Pleistocene right-lateral movement of at least 30 miles on the segment of the San Andreas fault extending from the western border of the Pearland quadrangle (long. 118°06′) to Cajon Creek (long. 117°26′), a distance of 42 miles. Discussion is confined to the San Andreas fault, and possible additional lateral movement on subparallel faults is not taken into account.

Because the record of movements on the San Andreas fault is fairly plain in the youngest formations and becomes progressively more obscure in older formations, this account begins with the latest events and proceeds to the earliest, the reverse of the usual historical order.

Several lines of evidence, none in itself conclusive but all pointing in the same direction, indicate that the total horizontal displacement on the San Andreas fault was of great magnitude. No accurate analysis is possible, and the estimated displacement of 30 miles since late Miocene time is considerably less than the estimate given by Hill and Dibblee (1953, pp. 447-448) for movement on a more northerly part of the fault during this same period. It should be noted, however, that the figure given here applies only to the San Andreas fault itself. If the speculation offered by Hill and Dibblee (1953, p. 453), that the San Gabriel and San Jacinto faults may be ancestral portions of the San Andreas fault can be proved correct, it is possible that the aggregate movement on these faults, could it ever be determined, would bring the estimates more nearly into accord. Movement on the Fenner fault, a third possible ancestor, ceased before the Punchbowl formation was deposited.

Recent Displacements. Almost everywhere along the San Andreas fault the younger alluvium is deformed into low ridges, small sinks, and discontinuous scarps. At many places in the fault zone it is warped into low anticlinal domes and undrained shallow depressions. Elsewhere, however, it is undisturbed.

Just east of the Pear Blossom Highway bridge over Big Rock Creek, a recent uplift of the creek gravel has produced a scarp that faces upstream; this scarp probably was formed during the Fort Tejon earthquake of 1857. Before the earthquake, Big Rock Creek crossed the San Andreas fault 600 feet east of its present channel and flowed north through Mountain Brook Ranch; the old channel is still traceable. It had been shifted to that position by right-lateral movements on the San Andreas fault amounting to 600 feet, prior to the Fort Tejon earthquake. The 1857 uplift across the channel diverted the stream back to a course in line with its original channel on the southwest side of the fault.

Where the San Andreas fault crosses Pallett Creek a recent uplift of the younger alluvium has produced a scarp that faces downstream. This scarp also was probably formed during the 1857 earthquake. As a result of the uplift, Pallett Creek is rapidly deepening its channel and dissecting a peat deposit that accumulated in Recent time in a depression south of the San Andreas fault ridge.

Although the San Andreas fault dislocates the younger alluvium in the fault trench, the trench itself is an older feature, for the alluvium was deposited in the trench after it was formed. The San Andreas fault ridge also is an older feature, for parts of it are buried under younger alluvium. Yet the ridge is younger than the older alluvium, because at places this older alluvium is involved in the faulting that formed the ridge. Clearly the trench and the ridge are the result of recurrent movements.

The older alluvium is cut by many faults in the San Andreas fault zone. All these breaks are expressed topographically and are readily traceable on air photographs; their scarps are degraded, however, and most of the fault trenches are floored with younger alluvium. On many faults the displacement of the surface is reversed abruptly from place to place along the fault trace, indicating a dominant horizontal component.

Three gaps in Holcomb Ridge represent stream valleys whose upper courses have been offset by the San Andreas fault. The easternmost, Bob's Gap, is the offset valley of Big Rock Creek; the middle gap, now occupied by the combined stream courses of Big Rock Creek and Pallett Creek, is the offset valley of Pallett Creek; and the westernmost gap, unnamed, is the offset valley of an unnamed large stream course northwest of Valyermo. Each of these offsets indicates a horizontal or strike-slip movement of more than a mile on the San Andreas fault, the land on the southwest side of the fault having moved relatively northwest. The offsets are of the same order of magnitude as those of Little Rock Creek and other large stream courses in the Pearland quadrangle (Noble, 1953) and of Cajon Creek in the Hesperia quadrangle (Noble, 1932, p. 357; 1933, p. 17).

The fact that Big Rock Creek now flows northwest in the San Andreas fault zone and passes through the middle gap in Holcomb Ridge is seemingly anomalous. Actually the stream could not long have maintained its course through Bob's Gap against the rising

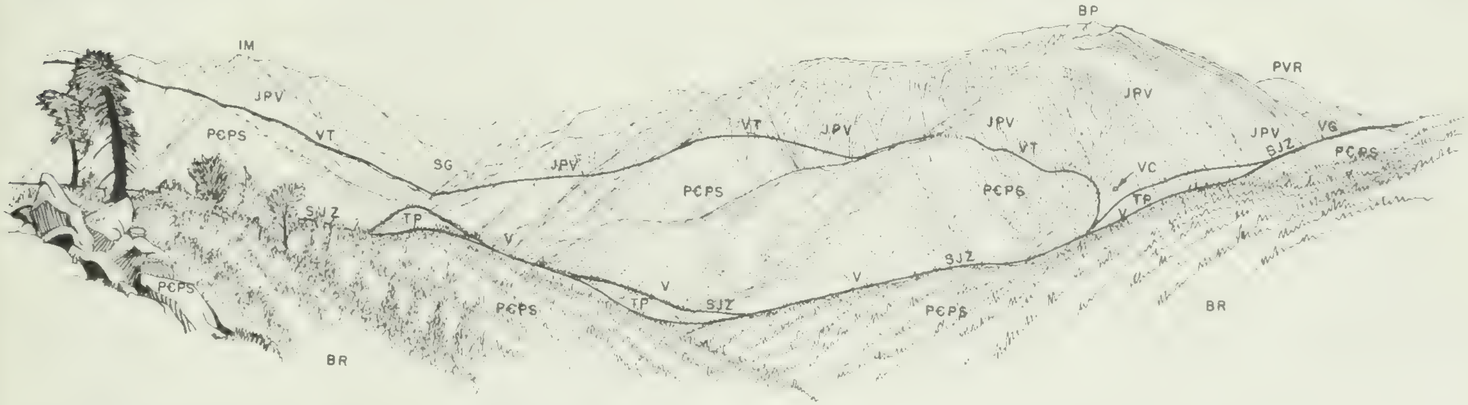

Figure 8. The Vincent thrust (VT); view down the canyon of the San Gabriel River (SG) in the San Gabriel Mountains from Blue Ridge (BR). A complex of heterogeneous plutonic rocks (JPV), which underlies Iron Mountain (IM), Mt. Baden-Powell (North Baldy) (BP), and Pleasant View Ridge (PVR), rests with thrust contact upon Pelona schist (PCPS). The thrust is truncated in Vincent Gulch (V) by the San Jacinto fault zone (SJZ) near Vincent Cabin (VC). Wedges of the Punchbowl formation (TP) occupy parts of the fault zone eastward from Vincent Gap (VG). *Sketch by Philip B. King.*

scarps of the Recent Hidden Springs and Holcomb faults and against the strong northwesterly tilt of the San Andreas fault trough on the flank of the rising San Gabriel Mountain arch.

An area of older alluvium north of the San Andreas fault between Pallett Creek and the Valyermo Ranch has no counterpart directly opposite on the south side of the fault, but the material is lithologically identical with the older alluvium south of the fault near the west border of the Valyermo quadrangle. In both areas the gravel consists chiefly of cobbles derived from the San Gabriel Mountains, without admixture of granodiorite from Pinyon Ridge nearby. The existing relation indicates a horizontal offset of the older alluvium of 1 to 2 miles.

Late Pleistocene Displacement. Toward the end of Harold deposition in late Pleistocene time, upwarp of the basement rocks of the northern San Gabriel Mountains into a broad arch caused them to shed debris northward in coarse alluvial-fan deposits all along the steepening northern flank of the mountains from the Palmdale-Little Rock area eastward to Cajon Pass, where the Shoemaker gravel forms the infacing bluffs at the summit of the pass (Noble, 1926, p. 419; 1933, pp. 18, 20). A check of precise levels run northward across Cajon Pass from the San Andreas fault in 1906, 1924, and 1944 shows that at least a segment of the arch is still rising, apparently at the rate of 20 inches per century (Gilluly, 1949, pp. 562-565). Some erosion may have intervened prior to deposition of the Shoemaker gravel, but no unconformity can be detected in most places, where the boundary between the Harold formation and the overlying gravel is essentially a change from finer to coarser material.

Movements after Harold time and before the older alluvium was deposited are indicated by the fact that the Harold formation and the Shoemaker gravel are more deformed than the older alluvium. Both lie flat in some places and dip gently in others, but locally they are considerably warped and folded, and in the San Andreas fault ridge they are violently disturbed. Both formations are cut by many faults that are parallel to the San Andreas or branch from it at low angles.

During this period the Harold formation may have been displaced as much as 5 miles by horizontal movements. Rocks of the Harold formation exposed north of the San Andreas fault west of Valyermo are lithologically similar to Harold strata exposed south of the fault 2 to 5 miles farther west, indicating a displacement similar to that of the same formation in the Pearland quadrangle (Noble, 1953).

Displacement Indicated by Anaverde Formation. Within and northwest of the area shown in plate 5, all exposures of the Anaverde formation of early to middle Pliocene age lie north of the San Andreas fault. In the Pearland quadrangle, at a point 3 miles west of Little Rock Creek, the formation lies unconformably upon quartz monzonite. The constituent materials of the formation are almost entirely quartz monzonite without admixture of material from sources on the south side of the San Andreas fault, whereas those of the juxtaposed Punchbowl formation on the south side of the San Andreas fault are derived exclusively from rocks that crop out on that side of the fault. The Anaverde formation, which is younger than the Punchbowl, should contain material from the Punchbowl formation or from the rocks south of the San Andreas fault zone if it had been deposited in the position that it now occupies, for cobbles weather out easily from the Punchbowl formation and are incorporated in great abundance in the Pleistocene Harold formation wherever it overlies the Punchbowl.

The evidence suggests that at the time the Anaverde formation was deposited, rocks other than those now adjacent were present on the south side of the fault. Thirty-five miles northwest of Palmdale, the Liebre quartz monzonite described by Crowell (1952a, p. 11), probably the equivalent of the quartz monzonite from which the Anaverde was derived, crops out south of the San Andreas fault.

Displacement of Punchbowl Formation. In the Valyermo area the strata of the Punchbowl formation north of the San Andreas fault do not match lithologically those of the same formation exposed in the Punchbowl trough directly opposite them to the south; but some of them match beds in the facies of the Punchbowl formation exposed south of the fault from a point 5 miles west of Valyermo to the Pearland quadrangle, several miles beyond. As interpreted by the writer, these relations indicate that the two facies of Punchbowl rocks have reached their present juxtaposition by horizontal movements along the fault.

A combination of geologic features north of the San Andreas fault within an area several miles square bordering Cajon Creek corresponds remarkably with a combination of geologic features south of the fault within and west of the Valyermo area (Noble, 1926, p. 420). On both sides of Cajon Creek, just north of the San Andreas fault, marine beds of littoral origin are lithologically similar to and correlated with the Paleocene Martinez formation of the Valyermo area and overlie basement rock similar to the granodiorite of Pinyon Ridge, in the Valyermo area. The Martinez beds at Cajon Creek are complexly folded and faulted, and, as in the Valyermo area, are overlain unconformably by less complexly folded and faulted upper Miocene strata similar in lithology to the lower member of the Punchbowl formation of late Miocene age in the Valyermo area. Both at Cajon Creek and in the Valyermo area these overlying beds contain vertebrate remains that, according to Chester Stock (written communication, 1950), indicate an age of late Miocene near that of the Barstow formation, with a possibility that the fauna of the Valyermo quadrangle may be slightly younger than the fauna of the beds at Cajon Creek. The beds in both areas contain cobbles of volcanic rocks of the Vasquez formation, the only apparent source of which lies 4 to 10 miles west of the Valyermo area and south of the San Andreas fault. This offset of cobble-bearing beds from the source area of the cobbles is similar to that described by Crowell (1952b) as indicating large lateral displacement on the San Gabriel fault.

Although the basal part of the Punchbowl formation is in juxtaposition with Pelona schist for several miles along the San Andreas fault in Lone Pine Canyon, the Punchbowl contains very little material of the Pelona. If these formations had been deposited in or near their present position, they should be crowded with material of the Pelona schist; where they lie with depositional contact upon Pelona schist just southeast of the Valyermo quadrangle, they are rich in schist debris. The evidence suggests that, at the time the Punchbowl formation was deposited, rocks other than the Pelona schist now adjacent were present on the south side of the San Andreas fault.

Beds of limestone are rare in the Punchbowl formation. Three miles southwest of Cajon Pass a bed of algal limestone crops out on the north side of the San Andreas fault. A similar bed crops out south of the fault about 4 miles west of the Valyermo area.

Two miles southwest of Cajon Pass, and north of the San Andreas fault, a thin seam of lignitic material that has been prospected for coal is interbedded with yellowish and buff sandstone and dark shale in the upper part of the Punchbowl formation. A similar seam, also interbedded with yellowish and buff sandstone and dark shale, crops out in the upper part of the Punchbowl formation south of the San Andreas fault, just west of the Valyermo area; it also has been prospected for coal.

The relations just described suggest that the upper Miocene rocks north of the San Andreas fault near Cajon Creek have been displaced at least 30 miles relative to those on the south side of the fault (Noble, 1926, p. 420).

Displacement of Punchbowl Fault. It seems possible that the Punchbowl fault also has been offset 30 miles or more by the San Andreas fault. At a point 4 miles west of Cajon Creek the Cajon Valley fault (Noble, 1933, pl. 3) diverges northwestward from the San Andreas fault for several miles (plate 5). The Cajon Valley fault closely resembles the Punchbowl fault, in that it is a reverse fault with southwest dip and northwest trend, and, as along the Punchbowl fault, shattered basement rocks injected by quartz monzonite are faulted against the folded Punchbowl formation.

Pre-Upper Miocene Displacement. The faults and folds in the Martinez formation record a major disturbance that took place before the Punchbowl formation was laid down. Although the relation of these movements to the San Andreas fault is a matter of conjecture, the alignment of the faults and folds of the Martinez and of the structural trough in which the Punchbowl formation was deposited indicate that these structures are closely related to movements on the San Andreas. It seems probable that the ancient seaway in which the Martinez and Vaqueros formations are assumed to have been deposited also coincides with this trough, implying that it too was structural in origin and was related to movements on the fault. If this interpretation is correct, the San Andreas fault or its ancestral equivalent was in existence as a major structural feature at least as early as the beginning of Tertiary time.

The difference in the pre-Tertiary basement rocks on opposite sides of the San Andreas fault in the Valyermo area and throughout the 50-mile segment studied by the writer (Noble, 1926, p. 420) suggests that horizontal movements greater than those already described may have taken place on the fault in early Tertiary or even in pre-Tertiary time. It is even conceivable (Noble, 1932, pp. 356, 357) that horizontal movements on the San Andreas fault totaling more than 50 miles have pulled the similar rock masses of the San Gabriel and San Bernardino Mountains apart (fig. 1), but if evidence of this movement is to be forthcoming it must await a detailed study of the basement rocks that border the San Andreas fault.

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6. STRIKE-SLIP DISPLACEMENT OF THE SAN GABRIEL FAULT, SOUTHERN CALIFORNIA

By John C. Crowell *

INTRODUCTION

The San Gabriel fault, which trends northwestward subparallel to the San Andreas fault for a distance of about 90 miles, apparently has a right strike-slip displacement of approximately 20 miles. The evidence in support of this conclusion comes from a consideration of the present distribution of coarse clastic sediments with reference to their source areas, and is described briefly in this paper. Two independent masses of conglomerate and breccia were laid down next to the San Gabriel fault scarp during late Miocene and Pliocene time. These masses have been displaced laterally by almost continuous strike-slip movement on the fault, beginning at some time in the early late Miocene and continuing until about the end of the Pliocene. A more complete description of the argument has been published elsewhere (Crowell, 1952).

The San Gabriel fault zone extends through a large part of the Transverse Ranges, and belongs to the system of faults that includes the San Andreas and San Jacinto. On the northwest it presumably meets the San Andreas fault beneath the Frazier Mountain thrust, near the juncture of the San Andreas with the Garlock and Big Pine faults (Crowell, 1950, p. 1641; Hill and Dibblee, 1953, pl. 4). For the next 25 miles of its course from this region toward the southeast, the fault bounds the Ridge basin on the southwest. Between Castaic and the San Gabriel Mountains the fault crosses low hills with little topographic expression, and in this region it limits three oil fields on the northeast: Castaic Hills, Honor Rancho, and Placerita. Through the San Gabriel Mountains the fault is marked by a wide crush-zone, and separates basement rocks of very different types. In the west-central part of the range the fault zone branches; the south branch merges with faults along the south front of the San Gabriel Mountains, and the north branch leads eastward into a structurally complex area, as yet unmapped in detail, north of San Bernardino.

The topographic trace of the fault zone is quite straight and is marked by aligned canyons and notches eroded in the sheared and broken rock. The zone generally consists of several faults that separate attenuated slivers, some of which are three-quarters of a mile wide. As a whole it dips very steeply, but major faults within the zone dip at angles as low as 65 degrees, either northeastward or southwestward.

In addition to the strike-slip movement on the fault, with which this paper is primarily concerned, there appears to have been a large dip-slip component of as much as 14,000 feet in the area 10 or 12 miles northwest of Castaic (Eaton, 1939, p. 521; Crowell, 1950, p. 1643). Here a great thickness of Ridge basin strata is preserved on the northeast side of the fault, which dips toward these strata and hence is apparently a normal fault. Its principal movement, however, is probably strike-slip. At some other places, as at Castaic, the apparent dip-slip component is the opposite, the southwest side having moved downward.

GEOLOGY ALONG THE SAN GABRIEL FAULT

The 50-mile segment of the San Gabriel fault under consideration here extends from the vicinity of Frazier Mountain on the northwest to the west-central San Gabriel Mountains on the southeast. Although the geology along the fault is simplified on the map (fig. 1), it is shown in greater detail on the map sheets of the Ridge basin, the Eastern Ventura basin, and the Soledad basin, which appear elsewhere in this volume. On the southwest side of the fault and at its northwest end, near Frazier Mountain, the basement rocks consist of gneiss. Quartz diorite predominates farther south in areas that are not yet completely mapped. About 7 miles northwest of Castaic the basement rocks are overlapped by the Tertiary marine sequence of the nearby Ventura basin. South and southeast from this area of overlap, all basement rock southwest of the fault for many miles is covered by marine strata belonging to the Mohnian (upper Miocene) or older stages. Basement rock (gneiss) again reaches the surface in the western San Gabriel Mountains, about 18 miles along the fault from the area of overlap.

On the northeast side of the fault, Ridge basin beds (Pliocene) are exposed at the north and extend to within 5 miles of Castaic (fig. 1). These strata lie upon Paleocene and Miocene sedimentary rocks as far north as the Clearwater fault, and on gneiss and granitic rocks farther north. Southeast of Castaic, Miocene and Pliocene sedimentary formations are exposed at the surface, and outcrops of basement rock are unknown until the San Gabriel Mountains are reached. Throughout this distance all basement rock is covered by sediments at least as old as late Miocene (Mohnian). The nearest exposures of basement rock northeast of the San Gabriel fault in this region are found about 4 miles northeast of Castaic, and consist of schist

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and local patches of quartz diorite and gneiss that appear from beneath the Mint Canyon formation (upper Miocene).

The geology of the westernmost San Gabriel Mountains has been mapped recently by Donald V. Higgs (see Contribution No. 8, Chapter VII). His map, simplified here, shows a band of gneiss between the San Gabriel fault and a complex of anorthosite and norite. The anorthosite, consisting almost entirely of white plagioclase (An 39-46), and the norite, a dark altered hypersthene gabbro, are distinctive rocks and in southern California are known to crop out only in this area.

EVIDENCE FOR LARGE STRIKE-SLIP DISPLACEMENT

The present positions of two different masses of upper Miocene coarse conglomerate and sedimentary breccia, which crop out next to the San Gabriel fault, apparently require a strike-slip displacement on the fault of many miles. Each mass contains coarse clasts of basement rock types that were washed into place from sources across the fault. At present, however, the areas across the fault from each deposit are mantled by sedimentary rocks that are older than the conglomerates, which of course means that the basement rocks of these areas were not available as sources of clasts for the conglomerates. But with a lateral displacement of about 20 miles, exposed source areas of appropriate composition are lined up properly with respect to the derived sediments.

Anorthosite-Bearing Conglomerates. Southwest of the San Gabriel fault zone, and 4 to 6 miles northwest of Castaic, coarse conglomerates are interbedded in sandstone and siltstone of the Modelo formation, as shown on the large-scale inset map in figure 1. The conglomerates, which represent the Mohnian stage (upper Miocene), are composed predominantly of clasts of anorthosite, norite, and related rocks with some gneiss and granitic types, but lack clasts of schist and older sedimentary rocks. The thickest beds, with large clasts as much as several feet in diameter, lie next to the fault, and thin toward the southwest. In fact, they are not known on the surface beyond the map area. This facies change, supported by a few observations of current bedding and slump structures, indicates that the debris was washed in from areas across the fault to the northeast, and probably came from a source nearby.

The composition of the clasts clearly shows that exposures of basement rock must have lain in this general direction during the accumulation of the conglomerates. But this region is now covered by sedimentary rocks older than the conglomerates for distances of several miles northeastward beyond the fault. Surface mapping and well data in this region to date have revealed no basement rock that is not mantled by older sediments. Schist, gneiss, and granitic rocks are exposed 5 miles northeast of Castaic, but clasts of schist and granitic rocks are very rare in the conglomerates. A reconnaissance search for distances of about 20 miles to the northeast has revealed no basement terrane of anorthosite and norite, nor have such rocks been reported from this area by other geologists.

About 12 miles to the east, some coarse sedimentary breccias containing anorthositic debris crop out locally in the Vasquez formation (Oligocene or lower Miocene), but these breccias lie beneath the Mint Canyon formation (upper Miocene) and probably were not exposed to erosion during late Miocene time. In addition, the lack of clasts of other rock types in the vicinity of the Vasquez exposures makes it still more unlikely that the erosion of these deposits provided the anorthositic debris in the Modelo conglomerates.

But do some of the Pliocene sediments in the area conceal anorthosites and norites that might have contributed debris during Miocene time to the conglomerates? Pliocene rocks are present southeast of Castaic, but well data show that sedimentary rocks older than the conglomerates are present at depth. In the Ridge basin, Miocene and older sedimentary rocks probably underlie the Pliocene section as far north as the Clearwater fault, but the sub-Pliocene geology is unknown in the extreme northwestern part of the basin. Inasmuch as granitic rocks and gneiss are exposed around this small area, however, it seems unlikely that any bodies of anorthosite and norite are concealed.

A basement terrane with appropriate composition to serve as a source for the anorthosite-bearing conglomerates is present in the western San Gabriel Mountains, and study to date shows that most of the rock types are lithologically identical with the clasts. It is suggested, therefore, that the western San Gabriel Mountains was the source area for the conglomerates. It seems very unlikely that the boulders and cobbles of anorthosite were washed directly from the present position of the source area. First, the available evidence indicates that the conglomerates came from a nearby source to the northeast, instead of from a relatively distant source to the southeast. Second, sandstones and shales of about the same age as the conglomerates lie in the area between the conglomerates and the San Gabriel Mountains. It would be most unusual for the conglomerates to be separated from their source by contemporaneous finer-grained deposits.

The evidence at hand therefore indicates that the anorthosite-bearing conglomerates accumulated just southwest of and across the San Gabriel fault from the San Gabriel Mountains. Their present position, some 15 to 25 miles relatively toward the northwest, apparently requires this amount of displacement on the fault. It is of

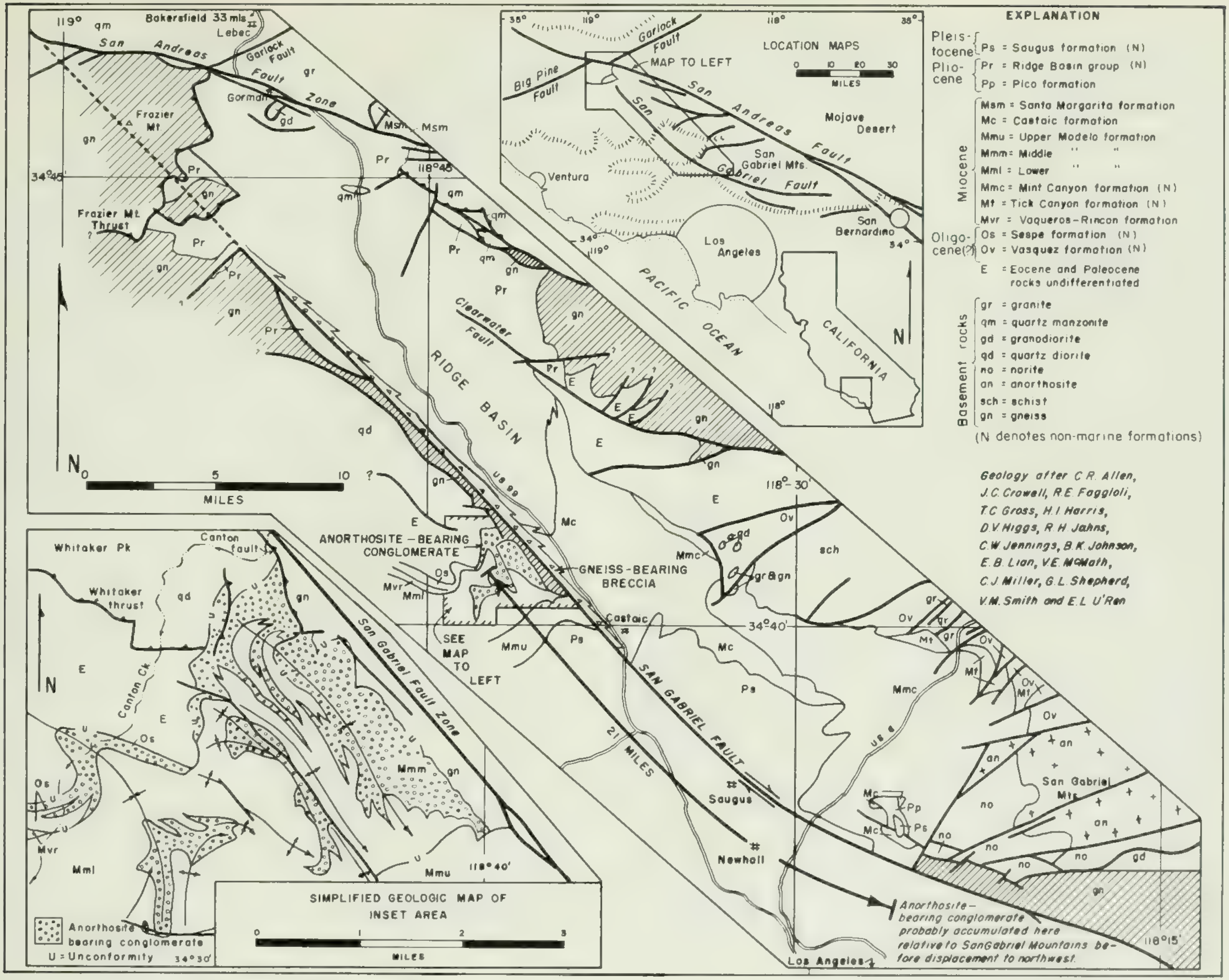
EXPLANATION
Pleis-tocene { Ps = Saugus formation (N)
Plio-cene { Pr = Ridge Basin group (N)
Pp = Pico formation
Miocene { Msm = Santa Margarita formation
Mc = Castaic formation
Mmu = Upper Modelo formation
Mmm = Middle " "
Mml = Lower " "
Mmc = Mint Canyon formation (N)
Mt = Tick Canyon formation (N)
Mvr = Vaqueros-Rincon formation
Oligo-cene(?) { Os = Sespe formation (N)
Ov = Vasquez formation (N)
E = Eocene and Paleocene rocks undifferentiated
Basement rocks { gr = granite
qm = quartz monzonite
gd = granodiorite
qd = quartz diorite
no = norite
an = anorthosite
sch = schist
gn = gneiss
(N denotes non-marine formations)
Geology after C.R. Allen, J.C. Crowell, R.E. Fagglioli, T.C. Gross, H.I. Harris, D.V. Higgs, R.H. Jahns, C.W. Jennings, B.K. Johnson, E.B. Lian, V.E. McMath, C.J. Miller, G.L. Shepherd, V.M. Smith and E.L. U'Ren
LOCATION MAPS
0 10 20 30
MILES
35° 119° 118° 35°
Garlock Fault
Big Pine Fault
MAP TO LEFT
San Andreas Fault
San Gabriel Fault
Mojave Desert
San Gabriel Mts.
Ventura
Los Angeles
San Bernardino
34° 119° 34°
PACIFIC OCEAN
CALIFORNIA
118°
N
119° qm Bakersfield 33 mls Lebec
San Andreas Fault Zone
Garlock Fault
Gorman
Frazier Mt
34°45'
118°45'
Frazier Mt. Thrust
Clearwater Fault
RIDGE BASIN
US 99
N 0 5 10
MILES
ANORTHOSITE-BEARING CONGLOMERATE
GNEISS-BEARING BRECCIA
SEE MAP TO LEFT
Castaic
34°40'
118°-30'
SAN GABRIEL FAULT
21 MILES
Saugus
Newhall
US 6
San Gabriel Mts
118°15'
Los Angeles
Anorthosite-bearing conglomerate probably accumulated here relative to San Gabriel Mountains before displacement to northwest.
Whitaker Pk
Canton fault
Whitaker thrust
Canton Ck
San Gabriel Fault Zone
118°40'
34°30'
Anorthosite bearing conglomerate
U = Unconformity
SIMPLIFIED GEOLOGIC MAP OF INSET AREA
0 1 2 3
MILES

FIGURE 1. Simplified geologic map of the Ridge basin and adjacent areas.

course impossible to determine just how much displacement has occurred, as it is not possible to work out details of the drainage pattern during late Miocene time and thus locate the conglomerate mass precisely with respect to its source area prior to displacement. It appears reasonable, however, to place the area of conglomerate accumulation somewhere within a 10-mile span that lay 15 to 25 miles relatively southeast of its present position.

The Gneiss-Bearing Sedimentary Breccia. Beginning about a mile northwest of Castaic, a narrow band of sedimentary breccia lies along the northeast side of the San Gabriel fault for a distance of 21 miles (fig. 1). Throughout its extent it consists predominantly of blocks of gneiss with minor amounts of granitic rocks, jumbled in an unsorted matrix, and it grades rapidly eastward into fine-grained sediments of the Ridge basin. The breccia, named the Violin breccia (see Crowell, Ridge basin map sheet, this volume), accumulated as a local deposit at the base of a fault scarp, and ranges in age from late Miocene at its base to late Pliocene at its top.

The southeastern 6 miles of this strip of Violin breccia, near Castaic, is separated from the sedimentary rocks of the Ventura basin by the San Gabriel fault. Here, too, it is composed predominantly of gneissic blocks that were derived from sources across the fault to the southwest. The area now opposite this breccia, however, is covered by sedimentary rocks that are older than the breccia. Although a narrow fault sliver of gneiss is now exposed in the fault zone, it must not have been available to erosion during latest Miocene time, as it is overlain unconformably by upper Miocene (Mohnian) strata. About 6 miles northwestward from the tip of the breccia belt, and on the opposite (southwest) side of the fault, quartz diorite with only minor amounts of gneiss and schist is exposed; judging from the predominance of gneissic clasts in the breccia, this terrane probably was not the source for the breccia. About 15 miles to the northwest the quartz diorite gives way to gneiss, and it seems more likely that the gneiss-bearing breccia accumulated opposite this part of the basement terrane. If so, the Violin breccia has since been offset about 15 miles by movement on the fault.

AGE OF MOVEMENT

Coarse sedimentary breccias containing anorthositic debris similar to that described above are present in the Sespe (Vasquez ?) formation (upper Oligocene to lower Miocene) in Canton Canyon, and they lie unconformably beneath the Modelo formation (see inset map, fig. 1). These rocks, which contain blocks of anorthosite several feet in diameter, show that a rugged source area lay nearby, presumably uplifted along the San Gabriel fault zone. Movement on the fault therefore may have been initiated during late Oligocene or early Miocene time, and certainly the fault was in existence by late Miocene time, when the anorthosite-bearing conglomerates of the Modelo formation (upper Miocene) were laid down. The relation of the gneiss-bearing breccia to the San Gabriel fault is even more clear, but the oldest part of the breccia probably was deposited somewhat later than the conglomerate.

Inasmuch as the Violin breccia ranges in age from late Miocene to late Pliocene, and appears to have required an adjacent steep fault scarp to account for its development, the San Gabriel fault must have been intermittently active during this complete span of time (Eaton, 1939, p. 522; Crowell, Ridge basin map sheet). Movement ceased toward the end of Pliocene time, as shown by the overlap of the fault trace by late Pliocene beds in the Hungry Valley area (Crowell, 1950, p. 1643). The fault must have been reactivated during the Pleistocene epoch, however, as it cuts Plio-Pleistocene beds in the region southeast of Castaic. Evidence of renewed movement also is present in the Hungry Valley area (Crowell, 1950, p. 1644). Information at hand, therefore, suggests that during the period of widespread mid-Pleistocene deformation in southern California, the San Gabriel fault was reactivated locally because it provided an already developed zone of weakness.

CONCLUSION

Two independent arguments for right strike-slip displacement of about 20 miles on the San Gabriel fault have been reviewed. Data now available seem to warrant this conclusion, but additional work in the area is required before the hypothesis can be proved. Basement terranes should be mapped in detail, and better sampling and comparison are needed to establish firm correlations between rock types in the conglomerates and breccia and those in the basement terranes.

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7. TURTLEBACKS IN THE CENTRAL BLACK MOUNTAINS, DEATH VALLEY, CALIFORNIA

By H. Donald Curry *

Introduction. The term "turtleback" has been applied by the writer to certain peculiar structural and topographic features in the central Black Mountains on the east side of Death Valley (Curry, 1938). The present paper is concerned mostly with a description of the three turtlebacks within this area. A few generalized conclusions also are presented, but much of the field evidence on which they are based must await fuller treatment in a more detailed account, still in preparation, of the complex geology of the central Black Mountains.

The area herein discussed extends from a point about 6 miles north of Badwater southward to the southern edge of the old Furnace Creek quadrangle (lat. 36° 00′), and embraces approximately 175 square miles of extremely rugged terrain. Altitudes range from —282 feet near Badwater to 6,384 feet at Funeral Peak. The mountains rise precipitously from the salt flats and alluvial fans of the valley floor and are dissected by deep, narrow, youthful canyons, the lower parts of which ordinarily are made impassable by dry waterfalls. The entire area contains only two or three perennial springs. Vegetation is limited to scattered desert shrubs, and bedrock is continuously exposed except where buried by talus or alluvium.

This general area, a portion of which is shown on figure 1, was mapped in detail by the writer during parts of 1938-41 and 1949. As no accurate base map was then available, two smaller areas that include the Badwater and Copper Canyon turtlebacks were surveyed by means of a plane table and telescopic alidade. The remainder was mapped on air photographs. Immediately to the south is the Virgin Spring area, whose remarkable geologic features have been mapped and described by Noble (1941).

General Relations. The turtlebacks are relatively smooth, curved topographic surfaces that have been developed on a complex of Archean metamorphic rocks and various intrusive rocks. These surfaces have been exhumed by the erosional stripping of material from an unusual overthrust surface, and consequently are structural as well as topographic features. They have plunging anticlinal and synclinal forms that apparently were developed by the folding and warping of a nearly planar surface. Their exposed dimensions are measured in miles, and their structural relief amounts to thousands of feet. Viewed from a distance the anticlinal surfaces resemble carapaces of turtles (fig. 2), and this appearance prompted their designation as turtlebacks.

Although they are thought to be present in parts of the Panamint Mountains and in the Funeral Range, the turtlebacks are best exemplified in the central Black Mountains. The three turtlebacks discussed herein are, from north to south, the Badwater, Copper Canyon, and Mormon Point turtlebacks (fig. 1). The Copper Canyon turtleback is the best developed and preserved, and can be considered as the type (fig. 2).

Any visitor to Death Valley who drives southward from Furnace Creek is likely to be impressed by the abrupt, precipitous, relatively straight western front of the Black Mountains, and by its border of young, symmetrical alluvial fans. Except for the Artist Drive Hills a few miles south of Furnace Creek, there are no foothills whatever. It is evident that the range front is a composite fault or faultline scarp along which movements of thousands of feet have taken place. Certain segments of the mountain front differ markedly from intervening segments, so that it is readily divisible into five units (fig. 1):

(1) From Furnace Creek southeastward to Natural Bridge Canyon the mountains consist of highly colored Tertiary sedimentary and volcanic rocks that are structurally complex but in general dip northeastward. The west face is bordered by the fresh, slightly curved scarp or scarps of the Artist Drive fault, which transects the strike of the Tertiary rocks.

(2) From Natural Bridge Canyon to Badwater the west face of the range is the Badwater turtleback, a remarkably smooth, curved, and only slightly dissected surface that is underlain by Archean gneiss.

(3) From Badwater to a point just south of the mouth of Copper Canyon, the front is bounded by a sharp, somewhat arcuate fault, and the rough, precipitous face of the range is an eroded fault scarp of brecciated pre-Cambrian (?) igneous and metamorphic rocks, and brecciated Tertiary granitic, volcanic, and sedimentary rocks, all in great disorder.

(4) South of Copper Canyon is another smooth, warped surface that forms a broad-nosed, northwest-plunging ridge and is underlain by Archean metamorphic rocks. This is the Copper Canyon turtleback. The trace of the turtleback fault swings abruptly into the mountains around the plunging nose, and bounds the Copper Canyon embayment on the south and east (fig. 2). This turtleback surface also forms the range front as far to the southeast as the mouth of Sheep Creek.

(5) From Sheep Creek the front trends successively southward, westward, and southeastward around the jutting promontory of

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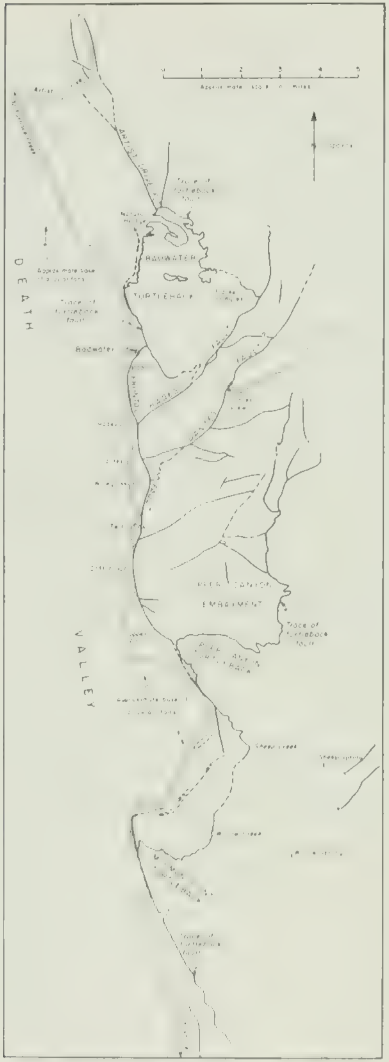

FIGURE 1. Map of central Black Mountain area, showing general pattern of faults and the relationships of the Artist Drive, Hades, and Frontal faults to the turtleback fault traces. The map is somewhat distorted, as it was made from an uncontrolled mosaic of air photographs.

Mormon Point (fig. 2). From Sheep Creek to Mormon Point and thence southeastward to the edge of the Furnace Creek quadrangle, the lower slopes of the mountains constitute a partly buried or dissected, partly well preserved surface. This is the Mormon Point turtleback.

Characteristic Features. Certain features are common to all three turtlebacks in the central Black Mountains, as well as to most of the others in the Death Valley region. The turtlebacks are not only distinctive topographic surfaces, but also are structural surfaces along which movement has taken place; that is, they are fault surfaces that can be referred to as the turtleback faults. Most of the overlying material, which consists of rocks that are softer or more brecciated than the underlying crystalline rocks, has been stripped away by erosion. In some places this material may have literally slid away as a result of recurrent movements of the hanging-wall block, but in most places it clearly has been progressively eroded away, leaving relatively untouched the more resistant crystalline rocks that lie beneath the turtleback surfaces. Relict masses of the hanging-wall rocks are preserved upon the turtlebacks, either low on the flanks of the anticlinal parts of the surfaces, in the synclinal parts, or as isolated islands on or near the crests.

The hanging-wall rocks range in age from Archean to late Tertiary, but are mostly Tertiary. They include older pre-Cambrian crystalline rocks, younger pre-Cambrian sedimentary rocks (Pahrump series), lower Paleozoic dolomites and quartzites, and various Tertiary sedimentary, volcanic, and granitic rocks. Some of the Tertiary sedimentary rocks in Copper Canyon can be dated provisionally as middle Pliocene by means of fossil mammal tracks (Curry, 1941).

At some places the rocks are as highly jumbled and chaotic as those of the chaos in the Virgin Spring area (Noble, 1941), and at other places they are relatively simple in structure. Most of the beds in the Copper Canyon embayment are structually simple. Close to the turtleback fault, however, there exists no semblance of bedding or other sedimentary structures for distances ranging from a few feet to 200 feet or even more. In this zone the rock is crushed, brecciated, and locally powdered. All pre-Tertiary rocks of the hanging wall, such as those of the typical chaos north of the mouth of Copper Canyon and those in places above the Badwater turtleback fault, are brecciated and disordered. Where pre-Cambrian crystalline rocks rest upon the turtleback surface, as near the mouth of Sheep Creek, they commonly are mylonitic. The surfaces of major movement—the turtleback faults or turtleback surfaces—everywhere truncate the bedding of the rocks in the hanging-wall block. Commonly the bedding dips into the adjacent turtleback fault at high angles.

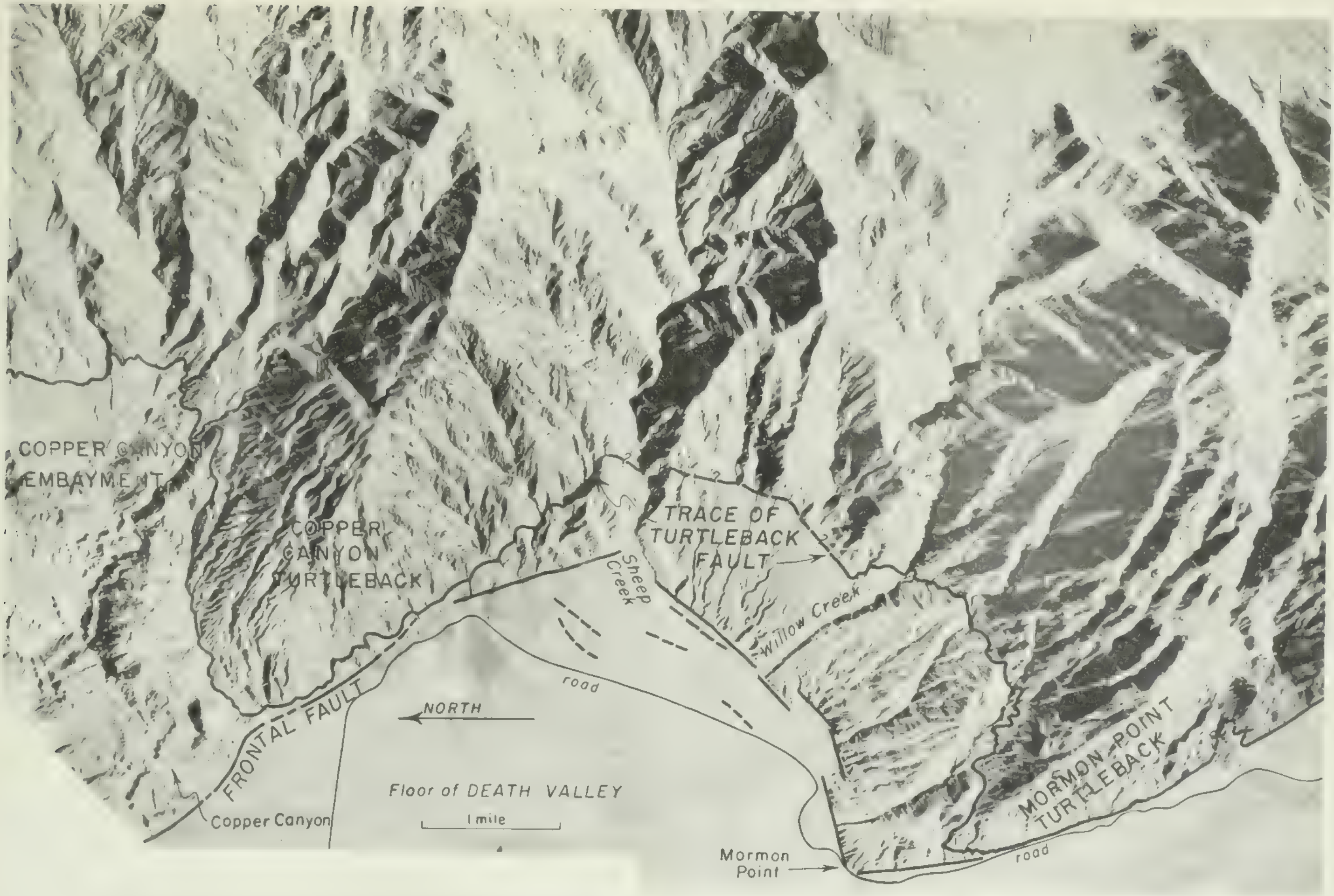

FIGURE 2. Mosaic of vertical air photographs, showing Copper Canyon and Mormon Point turtlebacks, Copper Canyon embayment, and traces of turtleback and frontal faults.

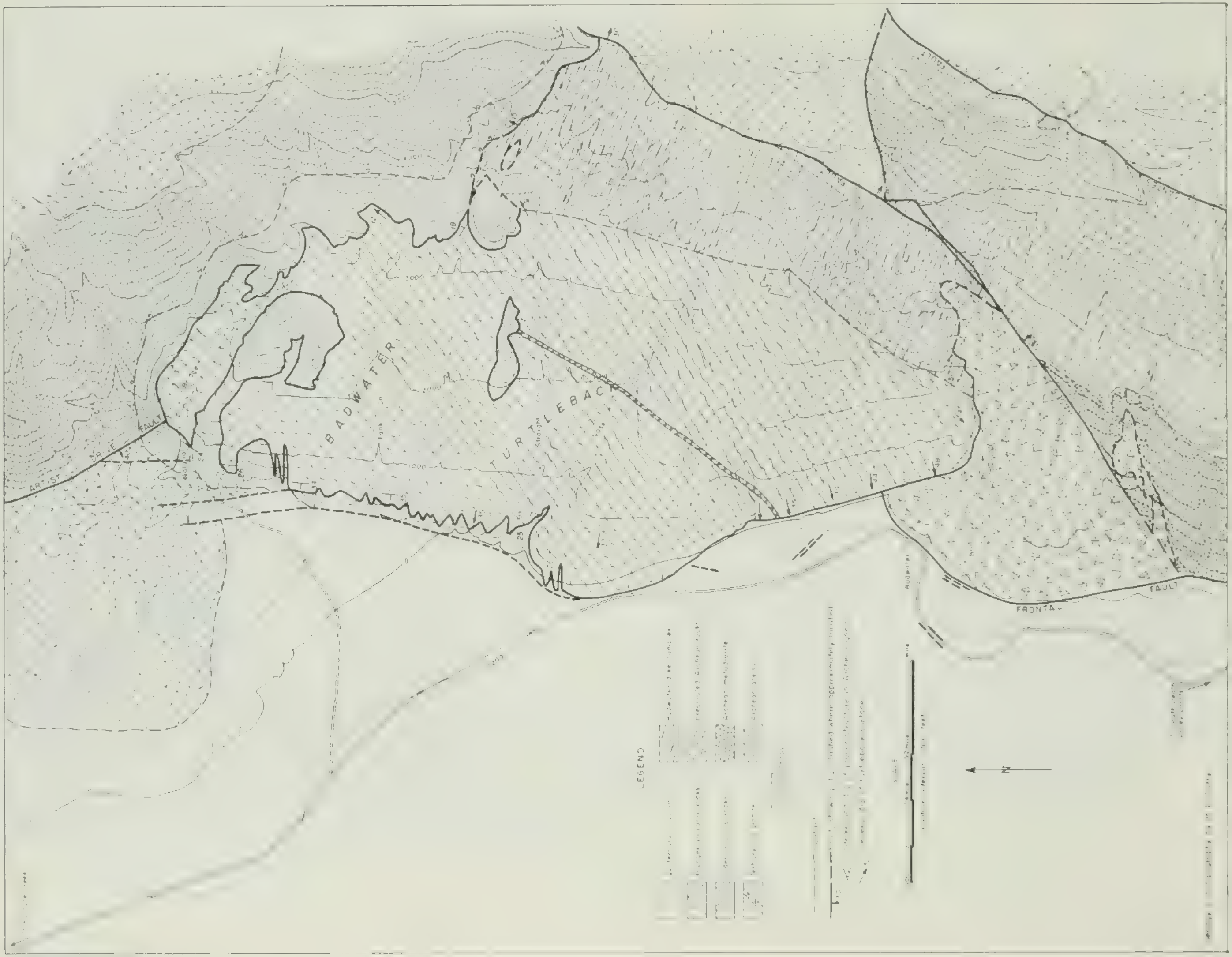

FIGURE 3. Geologic map of Badwater turtleback and adjacent areas.

The rocks that underlie the turtleback surfaces everywhere consist of older pre-Cambrian (Archean) rocks, together with irregular masses of intrusive rocks. The best-developed parts of the surfaces are underlain by well-foliated metamorphic rocks. Where they are not foliated, the Archean rocks commonly are brecciated, and the adjacent turtleback surface has been partly destroyed by erosion of this less resistant material.

In most places the turtleback faults are knife-sharp, and gouge is present either above or below the surfaces of movement. It ranges in thickness from a few inches to a hundred feet or more, but ordinarily is relatively thin. It consists of pulverized material that from place to place has been derived from rocks on the hanging-wall, the footwall, or both sides of the fault. Some include identifiable material that is not present in the nearby wall-rocks, and hence evidently was dragged from sources farther away. Most of the gouge is claylike and contains scattered angular or worn fragments of rock. It characteristically is vari-colored in pastel shades. It is cemented by calcite or gypsum, and veins of these minerals locally transect it.

Very small reverse or normal faults, with displacements of a few inches, extend into the gouge from the hanging-wall rocks, and its upper margin is thereby made very irregular. Associated with these faults are tightly folded pockets of gouge, which commonly are jammed into the hanging-wall rocks and lie above the main plane of movement. The fault surfaces locally show striations that trend at various angles to the strike of the turtleback surfaces, but that in general are oriented down their dip.

The turtleback faults appear to be parts of a single great break that once formed the sole of an overthrust plate, and the turtleback surfaces thus are essentially giant fensters in this plate. This conclusion seems inescapable, despite the fact that most of the various stratigraphic units in the hanging-wall block are younger than the pre-Cambrian rocks beneath the fault. That the turtleback surfaces are not attributable to normal faulting or landsliding is shown by their widespread occurrence and areal extent, by the chaotic structure, profound and apparently haphazard disorder, and intense crushing of the rocks that lie upon the surfaces, and by the low dips of large areas of the surfaces.

All three turtlebacks plunge to the northwest at angles of 20° to 25°. The axis of the main Badwater turtleback strikes about N. 20° W., although the axis of the subsidiary nose north of Badwater strikes N. 55° W. The crests of the Copper Canyon and Mormon Point turtlebacks also strike N. 55° W.

The dips of the turtleback surfaces range from less than 1° to 60°, but at most places they do not exceed 35°. Over large areas the dips are so low that they would seem to preclude movement by normal faulting along the surfaces, at least as they are now inclined. Neither could the typically convex turtleback shape have been produced by the intersection of two fault planes with opposing dips.

Shear planes or fractures in the rocks beneath the turtleback faults ordinarily are parallel or nearly parallel to the faults. Over wide areas this also is true of the foliation, although exposures in some canyons indicate that at depth the pre-Cambrian rocks commonly are contorted or broadly folded. Parallelism with the turtleback surfaces is most strikingly exhibited by the foliation of the metasedimentary rocks beneath parts of the Badwater and Mormon Point turtlebacks, where tabular masses of marble or lime-silicate rocks are exposed over large parts of the turtleback surfaces. Sill-like intrusive bodies of pre-Cambrian (?) diabase are similarly oriented at many places, and tabular masses of Tertiary (?) granitic and volcanic rocks tend toward such an orientation.

Numerous dikes of quartz monzonite porphyry, other granitic rocks, and various types of volcanic rocks intrude the pre-Cambrian metamorphic rocks and the ancient intrusive rocks that are associated with them. Most of the dike rocks probably are Tertiary in age. None of the observed dikes cuts a turtleback surface and penetrates the overlying rocks, even though many of them apparently are sheared-off feeders to bodies of volcanic rocks that once lay at higher levels. These dike rocks are lithologically similar to rocks that exist in various parts of the hanging-wall plate.

The best developed parts of the Badwater and Copper Canyon turtlebacks contain only a few widely spaced Tertiary dikes. High on the Badwater turtleback, however, is a remarkable dike swarm of granitic and volcanic rocks (fig. 3). In many places the volume of these parallel dikes is greater than that of the pre-Cambrian host rocks. Similar dike complexes occur elsewhere in the central Black Mountains. The Tertiary dikes of both the Copper Canyon and Badwater turtlebacks are nearly vertical and strike about N. 30° E. Those of the Mormon Point turtleback have not been sufficiently studied to permit generalizations concerning their structure and lithology.

The hanging-wall plates are cut by many faults that branch tangentially upward from the curved turtleback faults, and ordinarily steepen upward away from them. Few large faults and no small ones cut through the turtleback surfaces into the footwall rocks beneath. Although many faults do transect the footwall rocks, the only one observed by the writer to extend into the hanging-wall plate is the Hades fault, which apparently cuts transversely across the southeastern extension of the Badwater turtleback (fig. 3). The surface of this turtleback cannot be identified with certainty on the downthrown southeastern side of this major fault. Noble (1941) reports that several faults cut the Amargosa thrust in areas to the south.

The turtleback surfaces appear to be warped planes. They are inferred to have been originally flat or inclined at low angles, and to have been subsequently folded into plunging anticlines and synclines. Such folding is indicated by the broader attitudes of the material in the overlying plate. Although this chaotic material has a complex internal structure and is discordant and brecciated near its contact with the turtleback faults, it appears to be preserved as a discontinuous blanket above the turtlebacks, and to have been folded as a unit in rough accordance with the underlying faults. This is best shown in the Virgin Spring area, where less stripping of the fault surface has occurred, but it also can be seen in the Copper Canyon embayment and elsewhere in the area under discussion.

The Badwater and Copper Canyon turtlebacks have the form of northwest-plunging noses. If they once plunged in the opposite direction, evidence of this has been destroyed by movements on major faults or by erosion. The Mormon Point turtleback, however, is thought to be a complete anticline whose extension to the southeast has been mapped by Noble (1941) in the Virgin Spring area as the Desert Hound anticline. The resemblance of turtlebacks to ordinary folds is further shown by the presence of subsidiary noses, such as the one about 2 miles north of Badwater (fig. 3), and by the broad, terrace-like flattening on the flanks of the turtlebacks. Examples of such flattening occur in an area just south of the eastern angle of the Copper Canyon embayment, and in a large area on the southwest flank of the Mormon Point turtleback at Scotty Canyon, south of the area discussed here.

Badwater Turtleback. The Badwater turtleback, although not the most representative of all the turtlebacks studied by the writer, is herein described individually because its geology can be conveniently shown on a generalized map (fig. 3), and because many of its significant features can be readily observed from the main road on the floor of Death Valley. The geologic interpretations of the writer doubtless will not be generally accepted without reservations, but a foot traverse along the trace of the turtleback fault as mapped would answer many of the questions that naturally will arise in the mind of the reader. This is definitely not recommended as a casual hike, however, as the terrain is extremely rugged and locally hazardous.

The turtleback fault has been mapped from its intersection with the Hades normal fault, 1½ miles east of the mouth of Bad Canyon, to the point where it is again cut by that fault on the topographic divide 2½ miles north of Dantes View (fig. 3). Thus it nearly circumscribes the area of the turtleback surface, a great part of which has been little altered by erosion.

Several islands of chaotic rocks are in well-exposed and undoubted fault contact with the underlying pre-Cambrian rocks, and thus further demonstrate that the turtleback surface is a stripped fault surface throughout. The chaos consists mainly of numerous types of highly brecciated or intensely crushed volcanic rocks, particularly along the western base of the range, but pre-Cambrian metamorphic rocks and Paleozoic (or possibly upper pre-Cambrian) quartzites and carbonate rocks also are involved. The contact between these masses and the less chaotic and disturbed rocks that lie above them commonly is gradational, and its position has been necessarily generalized on the map (fig. 3).

Scattered dikes of Tertiary volcanic and granitic rocks are exposed on the turtleback, and they become progressively more numerous to the east, where they form the remarkable dike swarm noted in an earlier paragraph. The turtleback surface, if it ever existed above the dike complex, is now entirely obliterated as a topographic feature. A similar complex of dikes occurs on the downthrown side of the Hades fault, except that here no pre-Cambrian metamorphic rocks have been observed; the relationships between the two areas consequently are obscure.

On the south side of lower Hades Canyon is an indistinct contact of brecciated pre-Cambrian metamorphic rocks and associated intrusives with unbrecciated pre-Cambrian meta-igneous rocks. This contact may represent a continuation of the Badwater turtleback fault.

Normal Faults. The Artist Drive fault meets the Badwater turtleback at nearly a right angle where the strike of the turtleback surface swings eastward at Natural Bridge Canyon (fig. 3). The valley side of this active major fault is downthrown, and many features also suggest a strong strike-slip component in which the west side has moved relatively north.

The range front between the Badwater and Copper Canyon turtlebacks is the eroded scarp of a major normal fault, here provisionally named the Frontal fault. Its throw amounts to at least several thousands of feet, and scarps in the alluvium along its trace attest to its recent activity. At Badwater it joins the turtleback fault at an angle of 70°, and south of Copper Canyon it joins the turtleback fault tangentially; however, it does not cut either of the turtlebacks. This suggests that the plane of the Frontal fault may coincide with the turtleback fault at depth, and that there may have been recurrent normal movement on the west flanks of both turtlebacks.

Small Recent faults cut off the bases of the triangular interstream flatirons of hanging-wall material that are perched low on the southwest flanks of both the Copper Canyon and Badwater turtlebacks.

These breaks may be related to the Frontal fault. Similarly, a Recent normal fault is tangent to the steep west flank of the Mormon Point turtleback. It continues northward and ends abruptly at Mormon Point, a mile or more beyond the point where the turtleback surface curves sharply eastward to form a plunging nose (fig. 2). Between Mormon Point and the southwest flank of the Copper Canyon turtleback is a group of small, active, en echelon faults, some of which separate the upper Tertiary rocks lying on the turtleback surface from the alluvium of the valley floor. These faults trend eastward from Mormon Point, thence northeastward, and finally northward to intersect the southwest face of the Copper Canyon turtleback at a low angle (fig. 2). Like the Frontal fault, these smaller features may indicate a late dip-slip movement on the buried surface of the turtleback fault, although some are more probably attributable to differential compaction of the valley alluvium.

Conclusions. The similarity of the turtleback surfaces to the folded Amargosa thrust, as mapped by Noble (1941) in the Virgin Spring area, would be obvious even if the Mormon Point turtleback were not continuous with the Desert Hound anticline. In the central Black Mountains the hanging-wall plate ordinarily is less chaotic than in the Virgin Spring area, and in some places sedimentary and volcanic rocks that overlie the chaos of older rocks (Virgin Spring phase) are much less disturbed. The two areas are very similar, however, in their general structural features.

The turtleback surfaces are thought to be parts of an overthrust, similar to the Amargosa, that has been folded and subsequently exposed over large areas by erosional stripping of the hanging-wall plate.

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GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER V
GEOMORPHOLOGY

1954

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San Francisco | Bulletin 170 | September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER V

GEOMORPHOLOGY

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Editorial Note:

CHAPTER FIVE deals with the nature and origin of the present landscape in southern California. This region is one of great topographic and climatic contrasts, and the results of current geomorphic processes would be complex even if the rocks of the region were relatively uniform and their structure were relatively simple. But the rocks of southern California show remarkably great ranges of composition, physical characteristics, and geologic history, so that the problems of geomorphic interpretation are many times compounded. A straightforward description of the major features of the landscape would be difficult enough to prepare, even if it were to involve no discussion of the processes that led to their development, and a satisfactory treatment of both form and genesis of the landscape for the entire region could not be made on the basis of data now available.

The nine contributions in this chapter deal with both general and specific topics, and are concerned as much with process as with description. They point up the need, in the full treatment of a given geomorphic problem, for detailed knowledge of the materials involved and for understanding of the processes that affected these materials. The distribution of the various rock types and the history of their deformation plainly are vital factors, as well.

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1. SOME PHYSIOGRAPHIC ASPECTS OF SOUTHERN CALIFORNIA[*]

By Robert P. Sharp[†]

Southern California is a land of physiographic abundances, contrasts, and peculiarities. The wide range of geological materials and structures, the considerable differences in climatic environments, the host of geological processes at work, and the recency of diastrophic events are the principal factors responsible.

PHYSIOGRAPHIC DIVISIONS

Several good physiographic descriptions of southern California are available (Hill, 1928, pp. 74-101; Fenneman, 1931, pp. 373-379, 493-508; Gale, 1932, pp. 1-2, 8-10; Reed, 1933, pp. 1-23, 267-268; Hinds, 1952, pp. 63-108, 185-215), and it seems pointless to add another by regurgitation of the same material. Readers interested in the location, size, trend, and inter-relation of landscape features can determine this from a few minutes' study of figure 1 skillfully prepared by Charlotte Bjornsson.

Southern California comprises several well defined natural provinces, which are discussed in Chapter II, but the region can be even more simply divided into three major parts: (1) the coastal area between the sea and the environs of the San Andreas fault, (2) the triangular Mojave Desert block between the San Andreas and the Garlock faults, and (3) the Basin Range country north of the Garlock fault. Following brief statements on these major divisions, three selected physiographic topics are given more detailed consideration.

The Coastal Area. The principal subdivisions of the coastal area are the Transverse Ranges, Los Angeles Basin, Peninsular Ranges, and the Colorado Desert. The Transverse Ranges locally give a strong east-west grain to the landscape, which is confusing to visitors. The Los Angeles Basin, separating the Transverse and Peninsular Ranges, is a broad downwarp filled with Cenozoic marine and continental deposits. The Peninsular Ranges comprise an irregular and complex highland sloping westward toward the sea, and the Colorado Desert features a great elongated depression containing Imperial Valley and the Salton Sea. The continental borderland off southern California is composed of deep basins and submarine ridges and banks, which in size, arrangement, and trend strongly resemble the topographic features of the adjacent land (Shepard and Emery, 1941, p. 9).

The coastal area displays a host of interesting physiographic features and relations, prominent among which is a marked topographic unconformity (Willis, 1925, p. 677) between a late mature erosion surface and the youthful slopes incising it. Remnants of this feature are widespread, and it seems likely that they represent the same episodes of geological history, although this has not been definitely established. The late mature topography is termed the Sulphur Mountain surface in the Ventura region (Putnam, 1942, p. 751) and, less suitably, the Timber Canyon surface in Santa Clara Valley (Grant and Gale, 1931, p. 38). It developed rapidly on areas of relatively soft Cenozoic rocks after the middle Pleistocene orogeny and prior to late Pleistocene uplifts.

The Sulphur Mountain surface is probably younger than remnants of an erosion surface or surfaces of even more gentle relief on areas of older crystalline rocks (W. J. Miller, 1928, p. 199). Many of these remnants were formerly attributed to the so-called Perris or southern California peneplain (Dickerson, 1914, pp. 259-260; English, 1926, p. 64), but later work makes one wonder if there ever was a southern California peneplain. Dudley (1936) presents data suggesting that the Perris surface, a remnant of the southern California peneplain, is actually an exhumed feature and therefore older than a higher erosion surface preserved on the tops of nearby mountains. These relations are hardly compatible with the concept of a single widespread peneplain (Gale, 1932, p. 2).

Features in the Peninsular Ranges formerly attributed to an extensive peneplain (Ellis and Lee, 1919, pp. 37, 49) have since been the subject of opposing interpretations involving differences in the basic concepts of W. M. Davis (Bryan and Wickson, 1931; W. J. Miller, 1935, p. 1553) and Walther Penck (Sauer, 1929). Briefly stated, this involves the question of whether erosion surfaces of low relief at various levels are the dislocated parts of a single surface or local features actually formed at the different levels. Something of the same problem enters in the instance of the subdued upland of the San Bernardino Mountains (Mendenhall, 1907; Vaughan, 1922, pp. 323-324). Is this an up-faulted part of an extensive erosion surface covering much of the western Mojave Desert (Hershey, 1902, pp. 4-5; Baker, 1911, p. 365) or is it a feature of local development?

The suggestion is offered that not enough attention is given to the possibilities of local pedimentation on areas of granitic[*] rocks. Surfaces of low relief bounded by steep slopes can be developed rapidly with respect to local base levels upon such rocks in the climatic environment of southern California. The coincidence between lithology favorable to pedimentation and some, if not most, of the erosion-surface remnants formerly attributed to a single peneplain is noteworthy.

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[*] Igneous rocks of acid to intermediate composition with relatively coarse granular texture are included under this term.

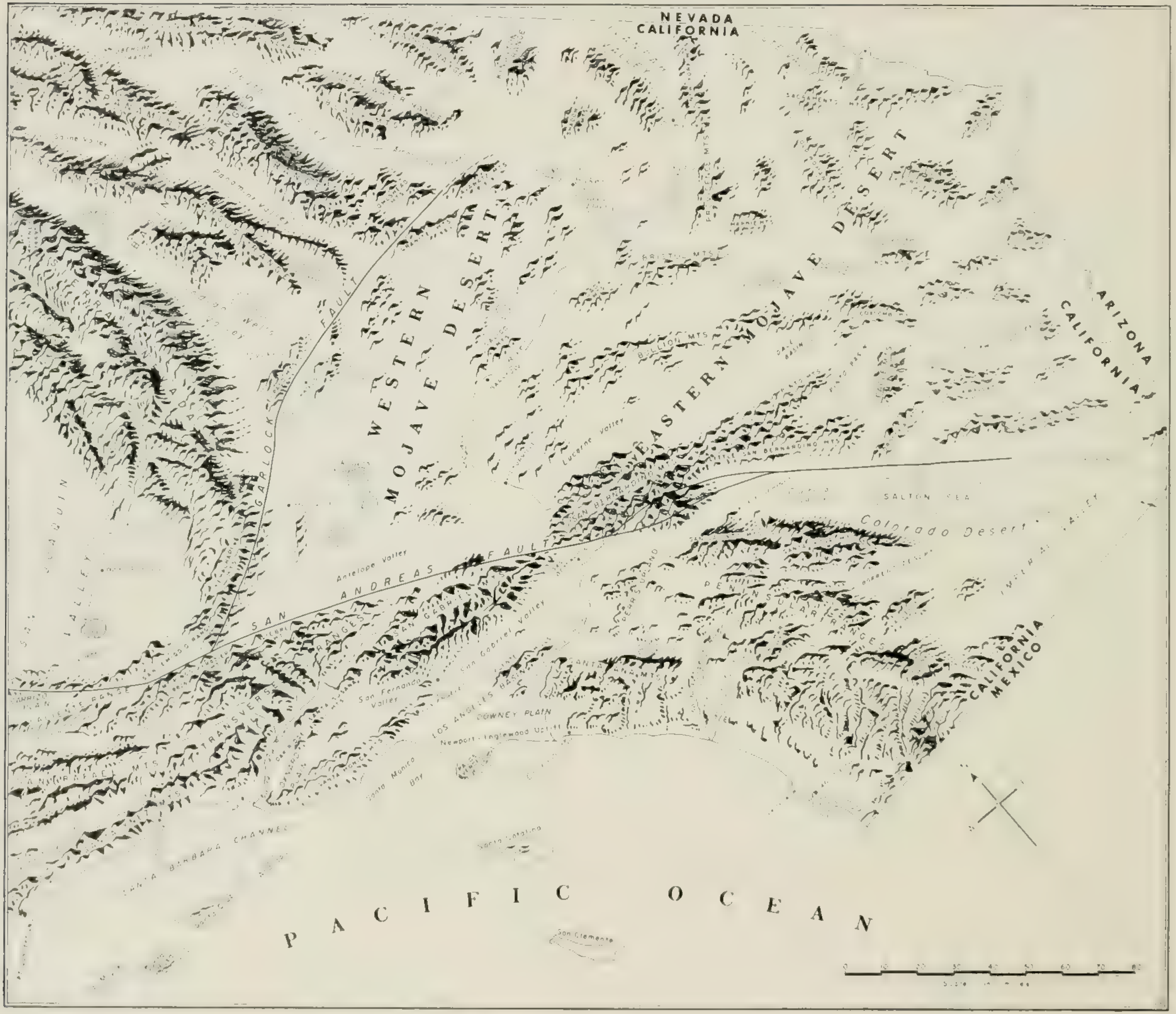

FIGURE 1. Physiographic diagram of southern California.

Within the coastal division the products of soil creep, earth flows, and landslides are widely seen on hill slopes underlain by Cenozoic sedimentary rocks, and this would be a good area in which to study the genesis and evolution of slopes on a wide variety of rocks and structures. A bare beginning has been made in this direction on slopes underlain by crystalline rocks (Strahler, 1950). The continental borderland off California provides excellent opportunity for investigation of submarine geomorphological features such as canyons (Shepard and Emery, 1941; Crowell, 1952), gullies, levees (Buffington, 1952), the continental terrace (Dietz, 1952), and many other features (Emery et al., 1952).

Mojave Desert. The north-south reach of the Mojave River separates the Mojave Desert into its two principal parts. The western Mojave is an area of predominantly low relief surmounted by a few isolated hillocks and low ridges. Davis (1933b, p. 245; 1938, p. 1359) considers it part of the Powell erosion surface, but this is one of those generalizations and oversimplifications that is difficult to establish or disprove by direct evidence. The area has unquestionably experienced much erosion, and it displays extensive surfaces of low relief on granitic rocks, but in the westernmost part it also includes wide flats underlain by alluvium. The eastern Mojave consists of mountains and basins which differ from the typical basin range topography by a lack of regularity in size, shape, and arrangement.

The Mojave country provides excellent opportunity for work on playas, alluvial fans, pediments, desert domes, relic and fossil soils, sand dunes, clay dunes, climbing dunes, falling dunes, yardangs, ventifacts, and the problem of eolian deflation. Desert varnish is widespread and deserves more extended study (Laudermilk, 1931), for its origin is not yet firmly established, and it may prove to have chronological value (Blackwelder, 1948). Casual observation also suggests that desert varnish may be a useful climatic indicator, for it appears to be deteriorating under present conditions in parts of the desert, possibly because of somewhat cooler and moister conditions following the post-Wisconsin xerothermic period.

Observers of desert forms do well to keep two principles in mind: (1) coarse granitic rocks are relatively non-resistant owing to their rapid disintegration, and (2) running water is remarkably efficient in the desert and contributes as much, perhaps more, to development of the landscape than it does in humid regions. This comes about because of the large supply of disintegrated debris available for transport, because of the concentrated nature of the runoff, and because the restraining influence of vegetation is small.

Basin Range Country. The region north of the Garlock fault, with its long narrow mountain blocks and corresponding basins, all trending in a northerly direction in classical basin-range fashion, differs markedly from the Mojave Desert to the south, and the boundary is sharply drawn by the fault (Noble, 1927, p. 35).

The Basin Range area provides good examples of upland erosion surfaces (Hopper, 1947, pp. 396-401; Maxson, 1950, pp. 101-103), geomorphic forms related to periodic uplifts of mountain blocks, fault scarps, fault scarplets in fans, some of the finest alluvial fans and cones in existence, extinct Pleistocene lakes (Gale, 1914; Blackwelder, 1933), and abandoned Pleistocene drainage courses (Hubbs and Miller, 1948, pp. 77-94; R. R. Miller, 1946). This area is also the home of the notorious wind-blown playa scrapers (McAllister and Agnew, 1948; Kirk, 1952; Clements, 1952; Stanley, 1953), and in Ubehebe Craters it possesses some of the finest dry maars on this continent.

THE ROLE OF DIASTROPHISM

A basic theme running through most of the major and many of the minor physiographic relations in southern California is Pleistocene deformation. This has been recognized in nearly all earlier physiographic treatments (Hershey, 1902, pp. 4-7; Mendenhall, 1908, pp. 14-15), but it deserves continued reemphasis. Faulting, folding, and warping have had a major hand in determining the size, shape, and arrangement of mountains and basins and even in some instances of ridges and valleys. With some exceptions, the principal functions of erosion and deposition have been to fashion details upon this diastrophically determined landscape.

Within the coastal area the middle Pleistocene orogeny is recognized as one of the most intense since the Jurassic (Reed, 1933, p. 273), and most of the principal landscape units were outlined or extensively modified at that time. Upfaulted, upfolded, and upwarped areas stand in relief not so much because they consist of resistant rocks, but because they have not yet been reduced by erosion. The belt of small en echelon domes and anticlines along the Newport-Inglewood uplift in the Los Angeles Basin affords good examples of folds so recently created that their present topographic form closely resembles the structure of the underlying materials (Hoots, 1932, pp. 27-29). In some instances alluvium is involved in this folding (Vickery, 1927, p. 423).

Diastrophism did not cease with the middle Pleistocene orogeny but continues to the present with the result that an impressive sequence of geomorphological developments is compressed into a remarkably short interval. For example, in the Ventura region the Sulphur Mountain surface was developed over a considerable area after the middle Pleistocene orogeny and then dissected in phase with repeated late Pleistocene uplifts separated by pauses during which terraces were cut along the sea and along rivers (Putnam, 1942, p. 751). The highest marine terrace now stands at an elevation of 1300 feet. A similar succession of events is known in the Palos Verdes Hills (Woodring, Bramlette, and Kew, 1946, pp. 113-117) and in southwestern Santa Barbara County (Dibblee, 1950, p. 19).

The desert region also displays considerable evidence of Pleistocene deformation. In the basin range country, recent fault scarplets break the alluvial fans at the foot of the mountain ranges (Noble, 1927, p. 39; Hopper, 1947, p. 398), and it is not difficult to imagine that Pleistocene faulting has played an important part in creating these ranges. In the Mojave Desert recent fault scarplets in alluvium are also common, but many of them are not closely related to the mountain blocks. This, plus the lack of consistent form and trend of the mountains, gives the impression that much of the present topography in the eastern Mojave is primarily the product of erosion acting upon a terrane of diverse rocks and complex structure. This focuses attention on the following problem.

Fully 60 percent of the eastern Mojave Desert consists of alluvium-filled basins about which almost nothing is known. Are these basins the product solely of erosion, solely of deformation, or a combination of both? Extensive studies of playa deposits in this area by the U. S. Geological Survey should eventually contribute to a solution of this problem. It is known that the alluvial filling in some, and perhaps most, of the basins is so thick that their rock floors are below sea level, and of course the same can be said for the surface of the alluvial fill in Death Valley. Thus, it is unlikely that these basins in their present form are solely the product of fluvial erosion. It is also difficult to imagine, in view of the alluvial filling, that eolian deflation has had much to do with creating the basins, although this has been advocated (Blackwelder, 1928). At some stage in geological history deposition has clearly exceeded erosion. This does not eliminate fluvial erosion as a possible and perhaps principal cause for the basins, but it requires a notable shift to deposition, to which climatic change may have been a contributing but not sole cause. Deformation must have played a part.

The evidences of recent faulting are so apparent in this area that the tendency is to think of faulting as the principal if not the only type of deformation. Warping is extremely difficult to detect in a region of rugged topography devoid of reference planes. However, in the region immediately east of Death Valley it is clearly recorded by Pleistocene lavas and fanglomerates and is one reason why Noble (1941, pp. 989-990) attributes a considerable part of the southern Death Valley depression to downwarping. Flexures are also recorded in late Cenozoic volcanics in the Ivanpah quadrangle mapped by Hewett (personal communication), and doming of an alluvial apron may be recognizable in the western Mojave (Wiese, 1950, p. 44). Other signs of warping were early recognized in the Mojave by Baker (1911, p. 367). Consideration should be given to the possibility that large erosional valleys in the Mojave region formerly draining to the sea have been deepened, dismembered, and subjected to alluvial filling by and because of warping just as much and perhaps more than by faulting.

A further word may be said about the role of warping in determining other topographic relations in southern California. It seems entirely likely that some of the highest and lowest parts of southern California mountain ranges mark the positions of broad transverse warps. In addition to features mentioned by Noble (1927, p. 32; 1932, p. 360) the San Gorgonio Peak-San Gorgonio Pass-San Jacinto Peak axis is directly aligned with the backbone of the Peninsular Ranges and may well represent a broad upwarp bearing slightly west of north. Reed and Hollister (1936, p. 96) remark on a somewhat similar relation extending into the Santa Ynez Mountains from the San Rafael Range, and Willis (1925, pp. 648-650) has called attention to arching in the California Coast Ranges.

PLEISTOCENE MARINE TERRACES

California marine terraces present a fascinating but difficult subject for study. They are well developed along the southern part of the coast from San Diego to Corona del Mar, in the Palos Verdes Hills, along the Santa Monica Mountains, in the Ventura region, and from Santa Barbara to Point Conception. As many as 15 to 20 terraces are recognized in some of these areas with elevations to at least 1600 feet above sea level. Most terraces have four principal features: (1) a sea cliff, (2) an abrasion platform truncating the bedrock, (3) a veneer of marine-laid detritus on the platform, and (4) a covering of terrestrial alluvium swept down from the highlands behind. This terrestrial coverhead attains thicknesses of as much as 150 feet and in places completely masks the topographic form of the terrace.

The greatest difficulty with terraces is the matter of correlation. This arises from the attempt to solve for two variables, namely eustatic shifts of sea level and deformation of the land, with only one known factor, the height of the terrace above sea level. Many of the earliest writings on California terraces ignored the possibility of eustatic shifts of sea level and attributed the terraces solely to uplifts of the land. The works of Davis (1933a, pp. 1044-1048) and Upson (1951, pp. 417, 444-445) clearly demonstrate the fallacy of this. Deformation of marine terraces has been recognized in the Palos Verdes Hills (Woodring, Bramlette, and Kew, 1946, p. 115), along the Santa Monica Mountains (Davis, 1933a, p. 1068), and in the Ventura region (Putnam, 1942, p. 739), but other parts of the coast are said to record no perceptible deformation of the terraces (Carter, 1950, pp. 93-95; Upson, 1949, pp. 108-112). Even local correlation of terrace remnants can be so difficult that reports of terrace deformation based on such correlations must be inspected with care. However, in the three areas listed above, deformation seems clearly established. In dealing with southern California marine terraces both eustatic and diastrophic influences must be considered; neither can arbitrarily be ignored. Furthermore, relations indicating whether a terrace was formed with respect to a stable, a rising, or a falling water level should be sought.

A common inclination in dealing with terraces is to think too much of the land features and not enough of the offshore relations. The latter are difficult to get at, but they are worthy of consideration since low-water stages may constitute at least half of the sequence along any coast. Some offshore cliffs, benches, and channels (Stearns, 1945, pp. 1072-1073; Upson, 1949, p. 108), and some onshore episodes of dissection (Ellis and Lee, 1919, p. 33; Upson, 1949; Carter, 1950, p. 92; Crowell, 1952, p. 66) are recognized and related to low-water stages, but more attention could be devoted to this matter.

To date, most terrace studies have consisted largely of measuring elevations above sea level. This is useful, necessary, and should be continued, but hopes for the future lie in giving more attention to the marine and terrestrial deposits mantling the terrace. Faunas in the marine deposits do not in themselves offer great hope of correlation (Woodring, Bramlette, and Kew, 1946, p. 105), but determinations of the absolute age of such organic remains may eventually provide a basis of correlation. Furthermore, the various phases of geological history recorded in the terrace deposits, especially the terrestrial coverhead, should aid in correlation. For example, a distinctive buried soil or marked episodes of channel cutting and refilling within the coverhead (Carter, 1950, pp. 92-101) may be recognizable in widely separated areas. Application of all the techniques of stratigraphy, geomorphology, and newly developed geochemical procedures bearing on geochronology and paleo-environments may eventually lead to successful terrace correlation.

The rewards will be considerable, for dated terraces can serve as time horizons over wide areas, and it should be possible to extend the chronology inland by means of river terraces. Properly correlated marine terraces can give an excellent measure of the amount and nature of late Pleistocene deformation along the coast and can contribute to an understanding of late Pleistocene geological events of all types.

ANTECEDENT STREAMS

Following Powell's (1875, p. 163) definition of an antecedent stream, the term was widely and indiscriminately applied to almost any stream transecting a ridge or mountain range. This loose practice and the discovery that the type example, the Green River across the Uinta Mountains, was not antecedent (Sears, 1924, pp. 282-304; Bradley, 1936, pp. 188-190) led to a reaction which too strongly discounted the principle of antecedence. The concept is sound, but airtight cases of specific examples are extremely difficult to find. A suggestion (Vickery, 1927, p. 422), that the close association of oil fields and antecedent streams in southern California warrants a careful watch for such streams on the part of petroleum geologists, invites the comment that oil fields may be easier to prove than antecedent streams.

The recency of deformation in southern California makes this a favored area in which to "prove up" some antecedent streams. A number have been reported as shown by the following partial listing: Los Angeles River across Dominguez Hills, San Gabriel River across the Puente Hills and the Seal Beach structure, Santa Ana River across the Santa Ana Mountains, Verdugo Canyon across Verdugo Hills, Ventura River across Red Mountain fault, Zaca Creek across Purisima Hills, small streams across Wheeler Ridge, and many others (Vickery, 1927, p. 421).

In some of the instances cited, deformation is so recent that one is predisposed to accept antecedence. However, streams also can assume courses across uplifts by: (1) superposition, (2) headward erosion, (3) spilling across divides for one of several reasons, and (4) localization along transverse structures, as suggested for one of the supposed antecedent streams noted above (Reed and Hollister, 1936, p. 114).

Criteria for establishing antecedence are obviously needed, but they are not easy to obtain, and in some degree the approach is negative for it involves eliminating alternative possibilities. Criteria should be sought along the following lines: (1) close conformity between the amount and nature of the uplift and the present landforms, (2) topographic, stratigraphic, or other lines of evidence suggesting that the stream flowed in approximately its present path prior to at least part of the uplifting, (3) deformation of terraces, gravels, or other stream features along the antecedent course. Recognition of antecedent relations in streams can be most useful with respect to geologic history, especially as to the time and nature of deformation.

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2. GEOMORPHIC PROCESSES IN THE DESERT

By Eliot Blackwelder *

Introduction. Of the geologic processes which operate on the desert surface, hardly any are peculiar to the desert. Some, like faulting and warping, are entirely unaffected by climatic conditions, but many others are strongly influenced by them, and so their effects are either more or less important than in humid regions. Some processes in the desert are controlled by climate directly. Others, like deflation, are more influenced by the nature and distribution of vegetation, which in turn are determined by the climate.

This paper deals with geomorphic processes in the desert region of the southwestern United States, a region that is not as extremely arid as parts of north Africa and northern Chile.

Diastrophism. There is ample evidence that earth movements, involving both warping and faulting, have played an important part in developing the scenic features of the arid southwestern states. In some areas the major features are probably due primarily to such movements. The origin of the characteristic desert basins, often called "bolsons," remains an unsolved problem, although there is basis for strong suspicion that diastrophism is an important factor. The difficulty is that earth movements are commonly very slow, and the features thereby produced are so greatly modified by erosion during their growth that the evidence of deformation is almost effaced.

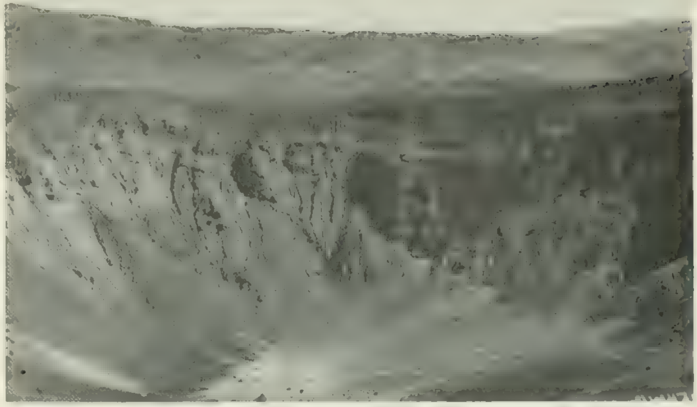

Figure 2. Interior of the main Ubehebe crater, in northern Death Valley. View east. The talus slope formed during the glacial epoch is now being destroyed by floods which are building fans below. A distinct unconformity is visible between the cindery material and the thin-bedded Tertiary sediments lower on the crater wall.

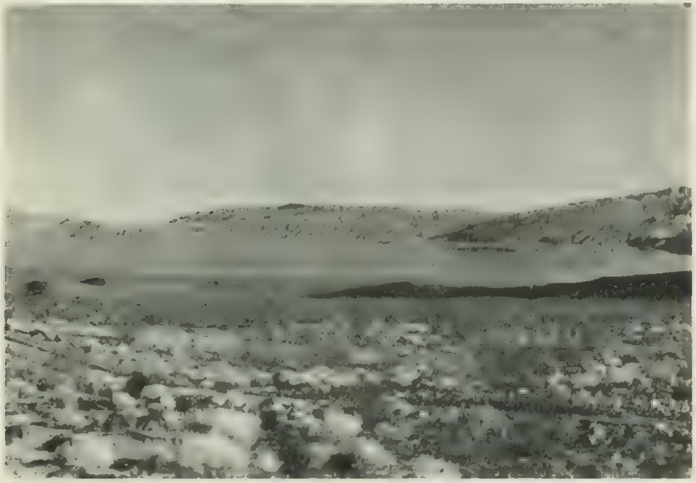

Figure 1. West slope of the Panamint Range, south of Townes Pass. The large fan on the right has been faulted in late Pleistocene time.

In such parts of the arid southwest as eastern California, the most easily recognizable diastrophic features are the low faultscarps that interrupt the basal slopes along some of the mountain ranges (fig. 1). One of the best known is the 20-foot scarplet near Lone Pine, formed at the time of the great earthquake of 1872. An even more striking feature is the narrow graben, bounded by parallel scarps, in the great alluvial fan 8 miles north of Ballarat, on the east side of the Panamint trough. There would doubtless be many more features of this kind were it not for the rapid progress of erosion, which has destroyed or greatly obscured those made before late Pleistocene time.

Indirectly rock deformation plays another important part in the geomorphic development of deserts as well as other regions. In the outer part of the earth's crust, which used to be called by Van Hise the "zone of fracture," orogenic movements produce intersecting systems of joints and also cause the development of rock cleavage.

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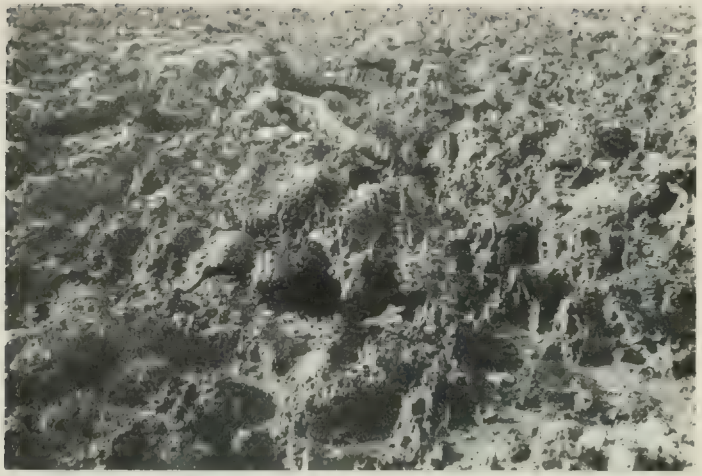

FIGURE 3. Detail of the salt plain in the bottom of Death Valley, showing effect of solution by rain. Width of foreground about 6 feet.

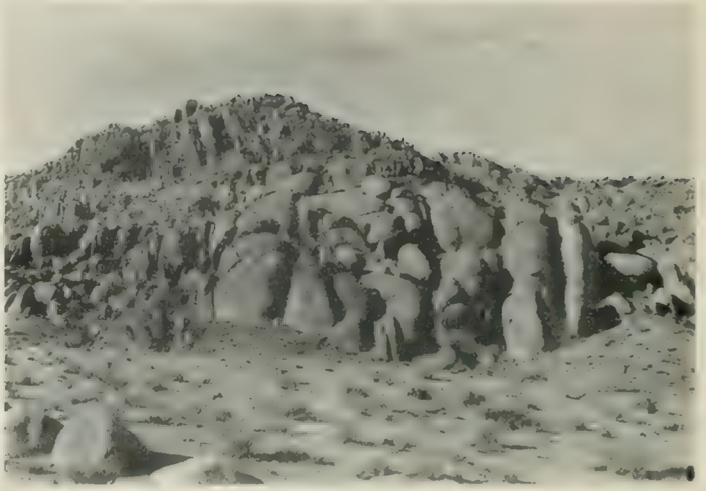

FIGURE 4. Effects of weathering and erosion on jointed granite, on the west side of Owens Valley.

Later, as the rising mass is worn down by erosion, the angular broken material is revealed at the surface and becomes part of the familiar load carried away by floods and the wind, thus developing into gravel, sand, and silt.

Volcanism. From late Tertiary down to Recent times, there has been considerable volcanic activity in the southwestern desert region of the United States, but erosion has left only the later Pleistocene and Recent volcanoes in recognizable condition. It is common to find small lava flows, each with a red or black cinder cone on its surface. Groups of these may be seen in the Amargosa Desert, around Little Lake, and northward along the east base of the Sierra Nevada. The Ubehebe group in northern Death Valley is unusual in that almost no lava was extruded, and the craters are surrounded by only a small quantity of cindery material (fig. 2).

Controlling Conditions. The severe climatic conditions and the peculiarities of surface vegetation in the desert have already been described in Chapter I. It remains only to emphasize certain matters that affect the geologic processes. Chief among these are the size and distribution of the desert shrubs, for these have an important influence on certain geomorphic agents. In extreme deserts the surface is devoid of vegetation, but in southwestern United States about the only barren areas are the dry-lake bottoms—the playas and salinas. Apparently these are places where seeds cannot germinate or where plants cannot endure the high concentration of salts in the groundwater. Elsewhere on the desert plains and hillsides, specialized hardy shrubs are scattered over the surface. On their height and spacing depends the effectiveness of deflation.

The desert is also characterized by the general absence of soil or any other type of regolith on the hills and mountainsides, because floods and winds remove all but the coarsest debris from the bare rocky surfaces. On the other hand the lowlands are covered with gravel and sand in transit.

Weathering. Contrary to beliefs prevailing a few decades ago, it now seems well established that chemical processes are vastly more important than purely physical changes, such as temperature variation, in the weathering of sound rocks in a desert climate.

On the surfaces of rather soluble materials, such as limestone and salts, rain and the moisture of dew promote solution at appreciable rates. The pits, hollows, grooves, sharp points, and ridges which result are so distinctive that they are easily recognized. The extremely rough surface of the salt flat in the central part of Death Valley is an outstanding example (fig. 3).

Because most rocks are susceptible to it, the process of hydration is of vastly greater consequence in the desert and appears to be the dominant factor in the weathering of many kinds of rock. Since the hydration involves expansion of the constituent crystals, the bonds between the mineral grains are broken and the rock disintegrates into sand and rubble. In the incipient stages of hydration the slight expansion of the exposed part of an outcrop or boulder tends to cause the separation of one or more shells from the interior of the rock, a process often called "exfoliation." In this way joint-blocks are converted into roundish boulders or wool-sack forms which are typical of granitic outcrops in arid regions (fig. 4).

Many things indicate the close relationship between the rate of disintegration and the availability of moisture to cause hydration. Thus slight cavities, holding moisture longer than surfaces exposed to sunlight, are progressively enlarged into niches. A granite statue in Egypt, fallen on its side, has disintegrated and exfoliated where the rock has remained in contact with the ground in which moisture is more prevalent, while the upper side, exposed to almost continual sunshine, shows no signs of alteration even after 3,000 years (fig. 5). Such instances at this indicate that insolation—the breakage of rocks by changes of temperature—is of negligible importance even in the hottest deserts.

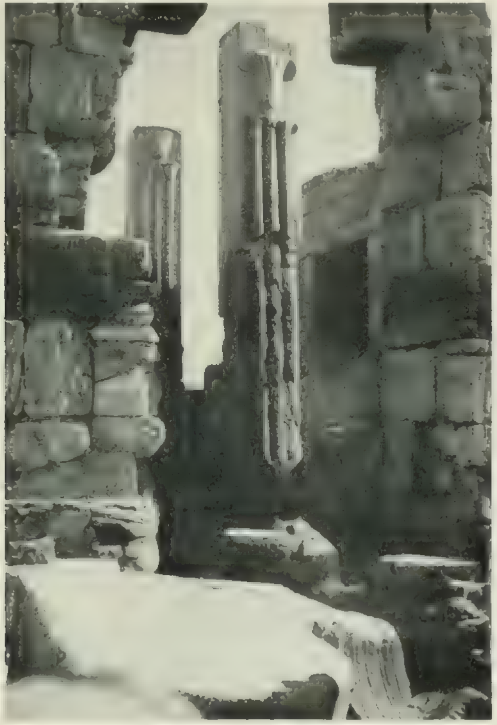

FIGURE 5. Granite columns in the temple of Karnak, near Luxor, Egypt. The lower part of the columns was buried in wet mud for many centuries, while the upper part remained continuously dry and therefore free from decay.

Because of the high temperatures and the scarcity of water at the surface in deserts, the mechanical wedge-work of freezing water is only a minor factor in weathering there. There is another type of wedge-work, however, which is more prominent in the desert than elsewhere, although effective only in special localities. It is due to the expansive action of salts crystallizing from brine solutions at or near the surface (fig. 6). This process is rapidly destructive to porous, fractured, or cleavable rocks swept down by floods to the margins of salinas, but it seems to be of little or no consequence elsewhere. Like frost action, it is incapable of breaking dense, sound rocks.

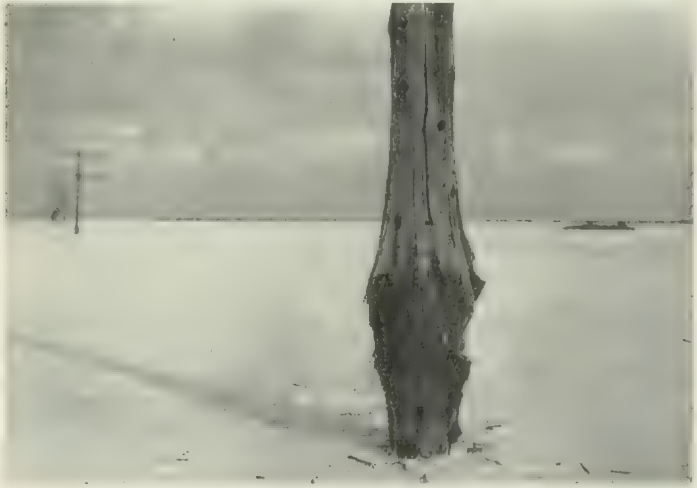

FIGURE 6. The effects of crystallizing salt on telegraph poles, in the salt flat east of Wendover, Utah.

Mention may be made here of another process involving ground water—that of cementation. In situations where there is a capillary rise of water just below the surface, there is a tendency for loose materials to become cemented by carbonates or other salts, forming the familiar caliche of the arid regions. Locally the result is a saline crust upon the surface, or a case-hardening of crumbling rock outcrops.

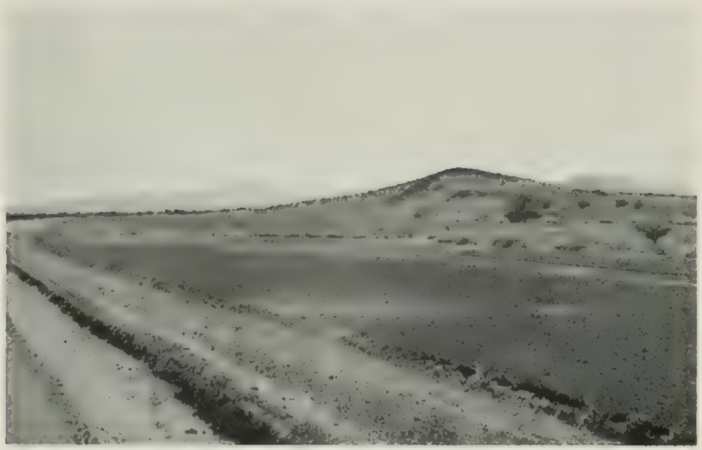

FIGURE 7. Typical desert pavement, blackened by desert lacquer, northeast of Yuma, Arizona.

Another process affecting exposed surfaces in the desert is the coating of rocks with a brown or blackish film consisting largely of oxides of iron and manganese. This desert lacquer (often called "desert varnish" or "patina") is characteristic of all hot arid regions (fig. 7). Although its origin is not yet fully understood, it now seems clear that it is not an exudation from the rock but that it has been slowly applied from the air by minute organisms, among which pollen, lichens, algae, and bacteria may participate. Because these organisms require an appreciable amount of moisture, the desert lacquer tends to be thicker in pits and small hollows on the rock surface. Observations in Egypt indicate that the formation of desert lacquer is so slow that it requires 2,000 to 5,000 years for a light brown coating and 20,000 to 50,000 years for a fully developed blackish layer. Hence one finds desert lacquer well developed only on upland surfaces which are not subject to occasional floods or to active sand-blasting.

Landsliding and Creep. Because of the general absence of soil, landsliding, creep, etc., are minor processes in deserts. They become rapidly more important in the marginal semi-arid regions. Locally along banks which are undercut by desert floods, rockfalls may be important, but as the heaps of debris are likely to be swept away by the next flood they seldom appear in the landscape.

The formation of taluses by the rolling of debris down from cliffs is of negligible importance in deserts because frost action is deficient and erosion by floods is far more rapid and effective.

Rubble Erosion. Rubble erosion, although only a minor type of erosion, is more important than is commonly realized. Along steep banks of unconsolidated gravel, such as terraces which are being undercut by the desert floods, rolling pebbles excavate round-bottomed chutes, rather than V-shaped gullies, and build evanescent talus cones below. Violent gusts of wind play an important part in dislodging the pebbles from the oversteepened bluffs. Rubble erosion is also an important aid to rill action on the slopes of many barren mountains.

Rain Pelting. In situations sheltered from strong wind action and floods, earthy surfaces are subject to vertical erosion by pelting raindrops and hailstones. The result is an abundance of tiny pillars, many of which are protected by small pebbles or even lichens. The beating rain also displaces loose mineral particles and contributes to their slow and ill-defined movement down the slope.

Sheet-Wash. When the surface receives during a rain more water than sinks readily into the ground, the excess moves downward as a thin sheet or plexus of rills. The latter tends to become concentrated in slight depressions and there forms distinct rivulets which in turn erode gullies. The sheet flood thus carries material down the slope as it becomes transformed.

Wind Action. As would be expected, wind action is more effective in deserts than elsewhere. While some work is done by ordinary winds, the occasional violent gales and the abundant daily whirlwinds do far more. Although the latter are relatively weak they are so frequent that their total effect is large. On a warm day in the desert a dozen or more whirlwinds usually can be seen in operation at any one time.

In general the desert is a region of deflation and suffers a net loss of material from its surface. Although some attempts have been made to measure the amount of this loss, the data are too scanty to justify more than guesses.

By the process of saltation the wind carries small pebbles a few feet above the ground. Sand is carried much higher, and dust is lifted thousands of feet into the air, whence most of it is exported from the desert. It seems probable that the volume of the dust carried in this way far exceeds that of the sand and gravel, although only the latter form distinctive features in the landscape.

In depositing its load, the wind sweeps fine gravel into windrows, seldom more than a foot high (fig. 8). Sand is heaped into drifts in the lee of obstacles or in suitably placed ravines, or is built into dunes of varied shapes (figs. 9, 10). Such accumulations are commonest on the lee sides of old lake bottoms or in atmospheric eddies localized by the surrounding mountains. It has been estimated that

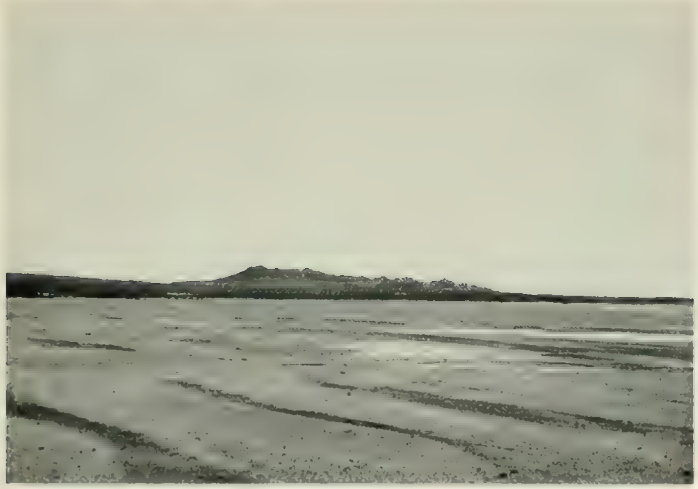

FIGURE 8. Windrows of fine gravel swept up on the northeast margin of Muroc dry lake in the Mojave Desert.

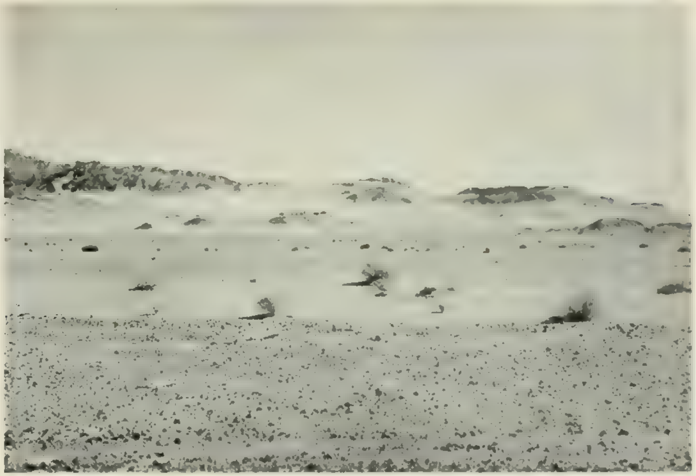

FIGURE 9. Low mountains partly buried in wind-blown sand, near Old Confidence Mill, in southern Death Valley. The widely spaced shrubs and the lag-gravel in the foreground are typical.

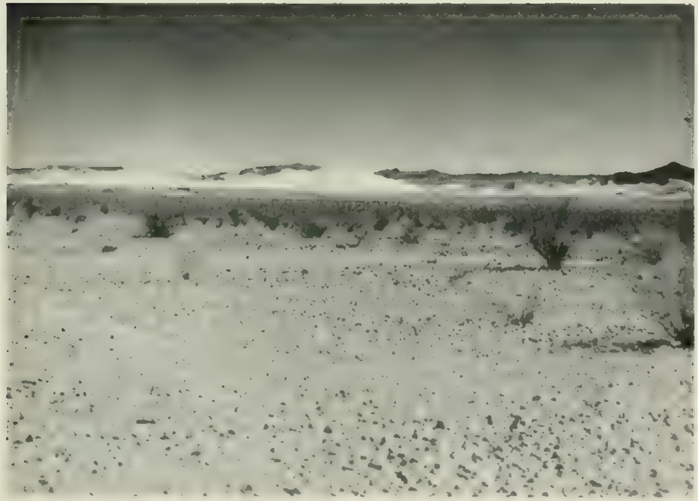

FIGURE 10. Large active sand dunes in southern Death Valley.

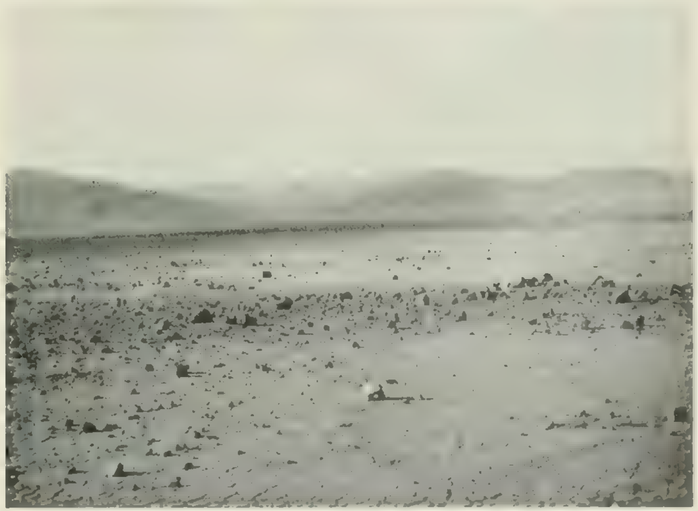

FIGURE 11. Residue of old bouldery mud-flow on the margin of a playa lake in the Mojave Desert. Deflation has removed nearly all fine material.

less than 5 to 10 percent of the surface of typical deserts is covered with such deposits of sand. The silt and finer sediments form thin mantles of loess on the slopes of the higher hills and mountains, wherever there is a protecting cover of vegetation, but most of it is probably removed from the desert altogether.

Deflation, being highly selective, sorts out the loose material according to size and weight. From surfaces unprotected by vegetation it removes all the finer material (fig. 11). Where the typical gravelly alluvium of a mountainous desert has been swept out upon a plain by floods, deflation winnows out the fine stuff, leaving only the larger pebbles. In time these form a continuous protective cover, often called a desert pavement or desert armor (fig. 7). Excavations show, however, that the pavement is only one pebble thick. These mosaic-like surfaces become so hard that a car driven across them leaves but a faint trace. As desert pavements seem to require many thousands of years to develop, they are characteristic of upland plains and terraces which are no longer subject to the action of floods. It is on these surfaces, also, that desert lacquer is usually well developed.

Although deflation has been shown to excavate hollows in the surface of the desert on a small scale, there is still the moot question whether it plays a minor or a major role in the excavation of the large desert basins. However, such depressions as that which contains the Kharga Oasis in Libya are very difficult to explain as being anything but deflation hollows.

As an incidental effect of deflation, a considerable amount of abrasive erosion is accomplished by the wind. It becomes important, however, only in those few localities where certain special conditions prevail. These conditions include (a) a surface nearly free from vegetation, (b) plenty of coarse sand or fine gravel, and (c) exposure to strong winds. Thus we find but little evidence of abrasion where the desert shrubs are spaced even 5 or 10 feet apart, and also but little effect on ridges, hilltops, and other places far removed from a supply of sand. Wind abrasion is most effective on the loose stones and pebbles lying on the desert plains, but it also chisels rock outcrops on the borders of such plains.

In the progress of wind erosion one can recognize several stages (figs. 12, 13). At first the rock surfaces are merely pitted and rendered dull, like artificially ground glass. The next stage is the development of many shallow grooves, rounded corners and incipient facets on pebbles. In the final stage abrasion develops distinctively shaped pebbles bounded by facets and rather sharp angles—the familiar dreikanter and other forms.

Where conditions are especially favorable and the wind is subparallel to the slope, the sand-blast may erase pre-existent ridge-and-gully topography and leave a nearly smooth slope (fig. 14). In case the wind is roughly parallel to a set of ravines and ridges, the former may be hollowed out into round-bottomed troughs leaving the ridges as sharp and even undercut prows or fins, called "yardangs" (fig. 15). In all these cases the so-called "sand-blast" has but little effect more than 1 or 2 feet above the ground, indicating that it is the fine gravel rather than sand which does most of the erosive work.

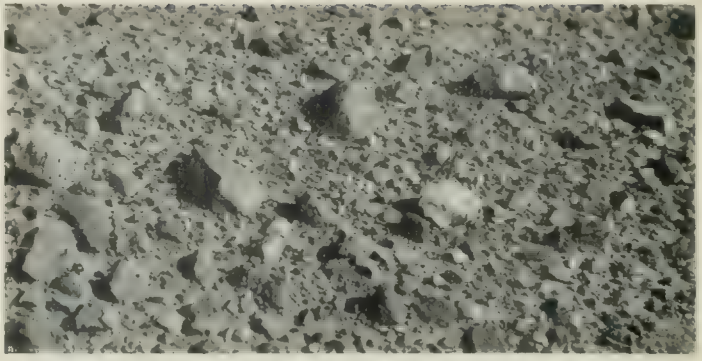

FIGURE 12. A detail of the desert pavement southeast of Stovepipe Wells, in Death Valley, showing numerous wind-carved stones.

The abrasive effect of the sand-blast becomes dominant over flood erosion only in extremely arid regions, such as northern Chile and Nubia, where the rainfall amounts to only a few inches per century and floods are very rare.

Stream Action. Aside from such exceptional rivers as the Nile and the Colorado, which are born in regions of considerable rainfall and merely traverse the desert on their way to the sea, the typical desert streams are rare floods developed quickly in otherwise dry channels and seldom lasting more than a few hours. The barrenness of the mountainsides permits the water to run off rapidly at times of sudden downpours and become concentrated in the bottoms of the ravines (fig. 16). This great increase in volume generates a high velocity, and both factors induce great erosive power (fig. 17). Although such floods may occur in any one valley only once in a decade or even a century, the effects may be greater than those caused by a continuously flowing river in an equal space of time.

As a result of floods in the desert, rock outcrops are severely abraded, the angular fragments swept down from the mountainsides are quickly rounded into pebbles, and, as a byproduct, a copious supply of sand, silt, and clay is produced.

On the steeper slopes of the hills such floods excavate abundant sharp ravines and gullies. Any soil or rubble is swept away, and no talus survives on the lower slopes. In the bottoms of the larger ravines and valleys, floods widen the channels and develop straths. These in turn coalesce into pediments (fig. 18), which may eventually expand over an entire mountain group, thereby forming a low dome, like the ones east of Mojave and possibly the Cima dome east of Baker (fig. 19; also see Sharp, Contribution 8, Chapter V). While the grading of pediments is in progress, remnants of spurs, in the form of isolated rocky mounds (called "monticules" by W. M. Davis), are left standing here and there. The gradients of pediments are usually between half a degree and 3 degrees, and average somewhat less than those of many alluvial fans.

Extensive observations in deserts show that two types of mountain slopes are prevalent. In one case the plain meets the mountainside in a smooth curve which is concave upward. This is probably governed by the action of rills and sheet-floods moving directly down the slope. In the other type the plain meets the mountainside abruptly in an angle which is commonly about 145°. Slopes of this kind seem to survive only where the mountainsides continue to be undercut by the occasional storm floods.

Where normal stream gradients have been dislocated by faulting or other accidents, the material washed out from the mountain canyons is spread out along the base, forming alluvial fans, as the flood streams attempt to reestablish their normal gradients. Since these fans have a general resemblance to pediments and were recognized earlier, many observers still confuse these two kinds of features. However, fans must be regarded as abnormal, whereas the pediment is the prevailing type of desert plain. Pediments invariably develop wherever conditions remain relatively undisturbed for a long time. Fans are usually more convex in cross-profile and commonly have steeper gradients than pediments. They belong to an early stage in the erosion cycle, whereas pediments expand as the cycle advances toward old age.

Although it might be expected that deltas would be found around the borders of the dry lakes in our deserts, very few have been identified. This may well be due to the fluctuating character of the desert lakes, which tends to cause the distribution of the delta material over a wide area.

Action of Mudflows. In the more severe deserts, where the annual rainfall is less than 3 inches, this process is of negligible importance. However, where the upper slopes of the mountains, enjoying a moister climate, are covered with enough vegetation to permit the accumulation of considerable soil material, or where deposits of unconsolidated earth are exposed on steep slopes, mudflows may develop (fig. 20). Hence their deposits are rather common in the alluvial fans along the bases of the higher mountain ranges, and they become much more important in the bordering semi-arid regions.

Erosion and Deposition in Lakes. Most desert lakes are temporary in character. Except after unusual storms, which occur only a few times in a century, they are generally represented by bare, dry plains, ordinarily called "playas." Such lakes do not persist long enough to allow the waves and currents to perform significant erosion along their shores. However, because perennial lakes existed in these basins during the cool and moist conditions of the late Pleistocene, it is not uncommon to find wave-eroded terraces, gravel bars, and other characteristic shore features around the sides of modern desert basins.

Contrary to a widespread supposition, the dry-lake bottoms are for the most part sites of deflation, and only intermittently are they subject to the deposition of sediments. As mentioned above, they are areas which suffer a net loss of material through the exportation of dust by the wind.

Although most of the lake bottoms in our arid southwestern states are underlain by hard baked clay, a few are covered with crusts of salt. According to Thompson the difference is due to the fact that, in the case of clay playas, ground water finds it possible to leak out of the basin to some lower place, whereas in the case of the salinas the only available exit for the disposal of the ground water which descends from the adjacent mountain slopes is through evaporation in the middle of the basin. Under these circumstances a crust of chemically complex salts, including chlorides, sulfates, and borates, covers the bottom of the basin. Searles Basin and Owens Lake supply good examples.

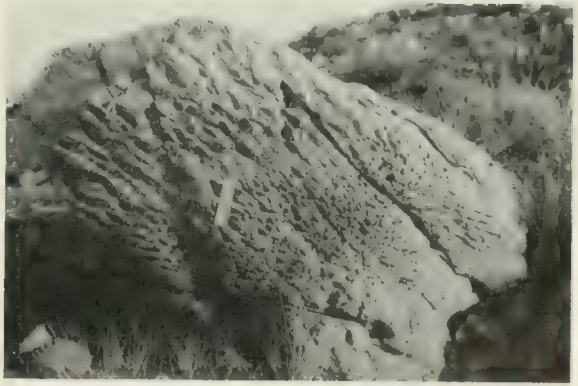

FIGURE 13. A boulder of granite drilled and grooved by intense sand-blast on hills east of Palm Springs, California.

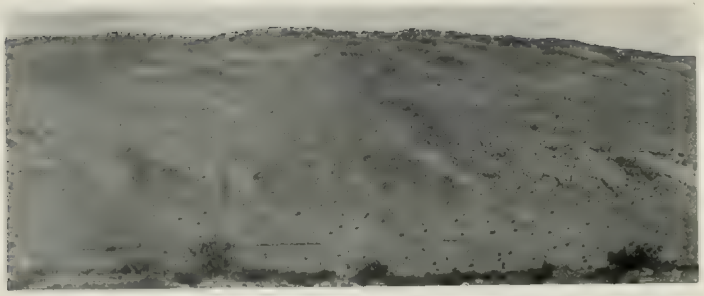

FIGURE 14. Effects of intense sand-blast action on a west-facing badland ridge, north of Edom, in the Whitewater Desert, California.

Complexities of Desert Processes. One can better understand the effects of the geomorphic processes of the desert if he bears in mind the fact that some of these activities alternate with one another, and also that the region has been subjected to important changes in climate during the last half million years. Only in the warm ages was it severely arid. In the cool ages the conditions of the steppe prevailed, and the surface was at least sparsely covered with vegetation.

Especially on the borders of the present desert area, the hills and mountainsides may be mantled with soil, rubble, or talus, a condition inherited from an earlier age of semi-arid or even temperate climate. With the onset of a warmer age, marked by increasing aridity and a dwindling cover of vegetation, this soil mantle not only ceases to be formed but begins to be eroded by floods and the wind. Such erosion forms gullies on slopes that were formerly smooth. Even talus slopes are gradually invaded by growing ravines, thus leaving only wedge-shaped remnants which in due time are entirely swept away, so that only the bare rock slopes remain.

On the other hand, the return to a cooler climate permits the process of creep to resume its action, thereby filling the gullies with rubble and soil and slowly restoring the former smooth surface. This alternating action of floods and creep seems to be the cause of the conspicuous rubble-stripes on many of the hillsides on the border of the desert.

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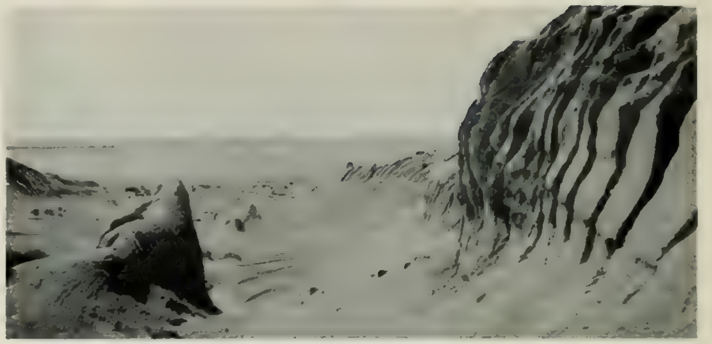

FIGURE 15. Wind-scoured troughs and yardangs, on the northeast side of Muroc dry lake in the Mojave Desert. The bottom of the trough contains much fine gravel in transit.

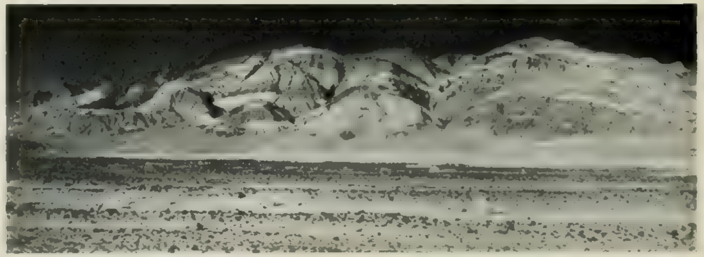

FIGURE 16. Scarp and alluvial fans east of the north end of the Panamint trough. The lack of soil is evident.

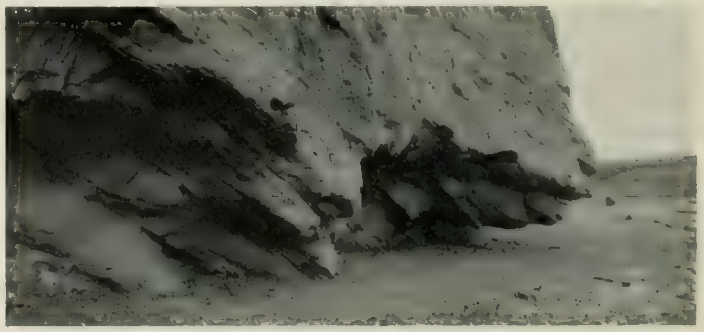

FIGURE 17. The effect of floods in undercutting rocky slopes, Furnace Creek Canyon, in Death Valley.

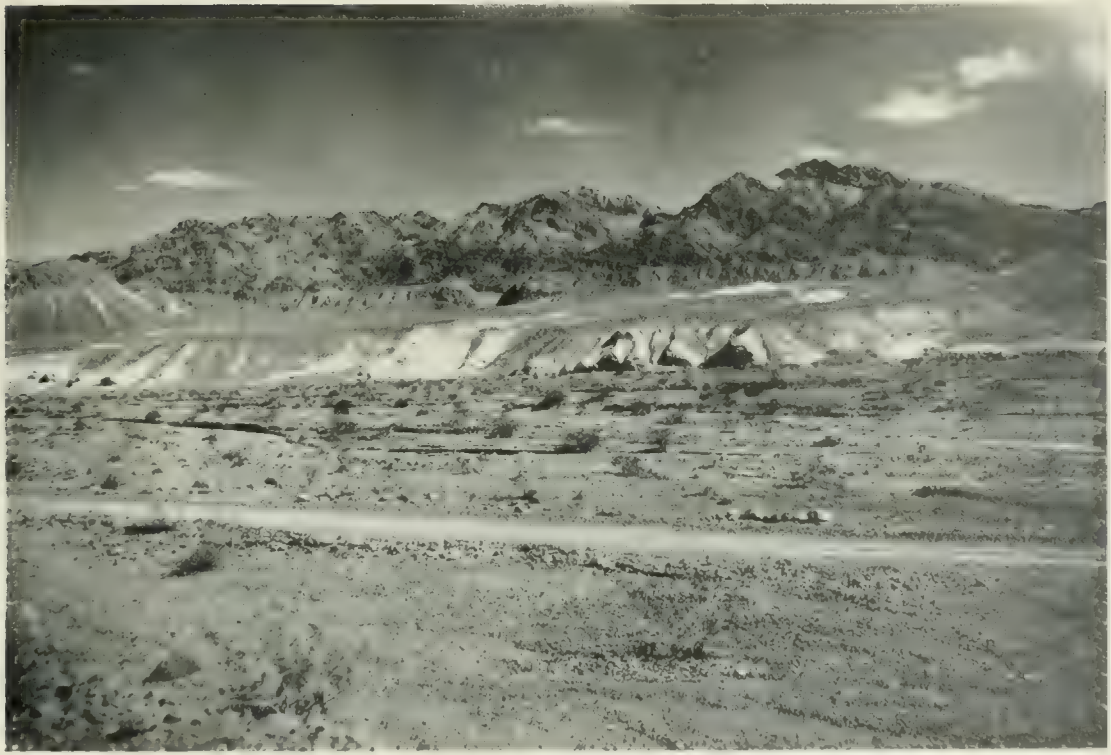

FIGURE 18. A dissected pediment, cut across inclined Tertiary beds, along the west base of the Funeral Range, east of Death Valley.

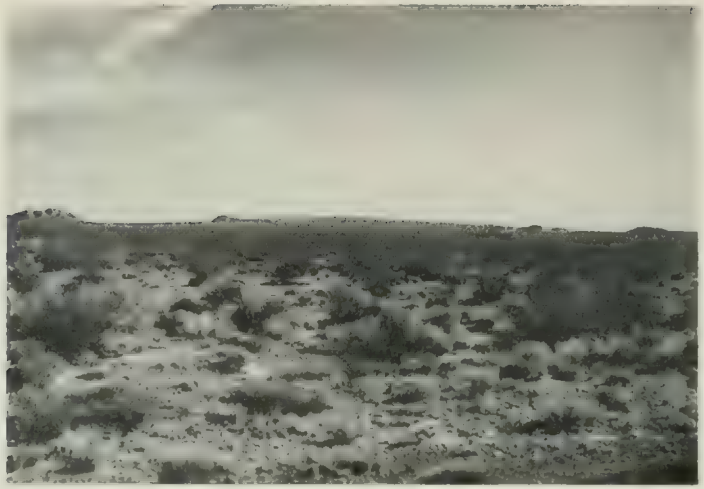

FIGURE 19. A panfan dome near Cima, with a few residual hills of hard metamorphic rock associated with the prevailing granite.

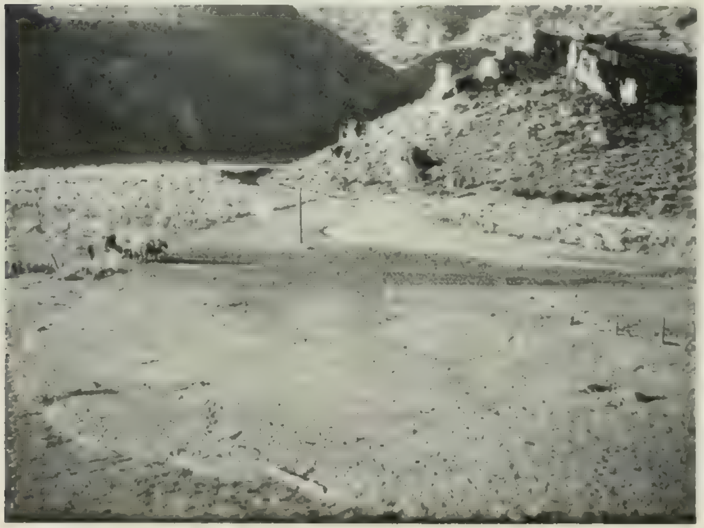

FIGURE 20. A fresh mud-flow from a tributary in Weber Canyon, Utah. *Courtesy U. S. Geological Survey.*

3. PHYSIOGRAPHIC FEATURES OF FAULTING IN SOUTHERN CALIFORNIA*

By Robert P. Sharp †

The abundance and variety of faults in southern California provide good opportunity for study of landforms created directly by faulting or indirectly by other processes acting upon faulted materials. High-angle gravity faults, high- and low-angle thrusts, and faults with large strike-slip displacement are present (see Chapter IV). Furthermore, all degrees and dates of activity are represented.

Landforms created by faulting can be classed as primary and secondary, or as original and subsequent (Lahee, 1952, p. 248). Primary features are those formed by actual fault displacement. They are nearly always modified by erosion, but should be classed as primary until completely effaced. Secondary or fault-line features are those formed solely by other processes acting upon faulted materials. Further subdivision into initial and modified primary forms and into erosional and depositional secondary forms would be possible, but it is not urged.

PRIMARY FAULT FEATURES

Fault Scarps. Southern California contains literally hundreds of fault scarps, a few feet to many thousands of feet high. Some of these scarps and the blocks, horsts, and grabens bounded by them, are the largest topographic features of faulting in the region. The Sierra Nevada scarp towers more than 10,500 feet above the floor of Owens Valley, the face of San Jacinto Peak behind Palm Springs is nearly as high, and the little-mentioned San Gabriel scarp near Cucamonga rises abruptly 6,500 feet above the alluvial fans at its base. The steepness of the scarps depends primarily upon their age and upon the nature and structure of the rocks composing them. The west face of the Black Mountains, sloping a good 35° toward the floor of Death Valley, is exceptionally steep for a major fault scarp in this region. A number of scarps steepen near the base because of rejuvenation by later uplifts, but some scarps along thrusts are steeper near the top owing to superposition of hard rocks on softer materials, for example the scarp of the San Cayetano thrust in Ventura County. Late Tertiary and Pleistocene thrusts are abundant in southern California, and many of those of high angle are marked by primary thrust scarps (Kerr and Schenck, 1925, p. 480; Cotton, 1950, p. 728).

In general, the height of a scarp indicates the minimum vertical displacement, but along a fault of large strike-slip displacement crossing rugged topography, this may not be true. It is possible that the south face of the San Bernardino Mountains was created by an oblique slicing apart of the San Gabriel-San Bernardino uplift along the San Andreas fault (Noble, 1932, p. 356). Smaller scarps formed by lateral displacement of hillocks and ridges can be seen along the Garlock and San Andreas faults.

Triangular Facets. Triangular facets, truncated spurs, and related forms are remnants of a fault scarp dissected by transverse streams and as such hardly warrant the extended attention accorded them in the literature. Fine examples of large triangular facets are seen along the west base of the Panamint Range (Hopper, 1947, p. 399) and on the west face of the Black Mountains east of Death Valley. The Black Mountain facets should not be confused with stripped remnants of a folded thrust, locally known as "turtlebacks," also seen here (Curry, 1938b; see also Curry, Contribution 7, Chapter IV).

Fault Scarplets. Owing to the recency of faulting, low scarps in alluvium are common and widespread. Piedmont scarplets break alluvial slopes at the foot of many mountain ranges, especially in the Basin Range region north of the Garlock fault, but they are not limited to this setting and in the Mojave Desert are found well out on the valley or basin floors. Most scarplets are a few feet to a few tens of feet high, but the Raymond scarp displaces the Pasadena alluvial apron by fully 100 feet near the Huntington Hotel. The height of a piedmont scarplet reflects in part its susceptibility to erosion by streams flowing from the mountains. Near Cucamonga, piedmont scarps 250 feet high in interstream areas record the sum of repeated fault movements, while lower scarps nearer the streams measure only the latest displacement (Eckis, 1928, pp. 229-230). An irregular trench along the base of many recent piedmont scarplets is probably produced by settling of loose debris along the fault trace.

Most piedmont scarplets face outward from the mountains, but some are back-facing, a good example being along the Garlock fault near Garlock station (Dibblee, 1952, p. 39). This particular back-facing scarp appears to have been formed by lateral offset of a higher part of the fan, but other back-facing scarps are produced by relative upward movement of the valley block. Shallow grabens are created in alluvial aprons by opposed piedmont scarplets, as beautifully demonstrated along the west base of the Panamint Range at the mouth of Wildrose Canyon (Noble, 1927, p. 39; Maxson, 1950, p. 104). A small lake south of Lone Pine in Owens Valley occupies a similar graben formed in part at the time of the 1872 earthquake (Hobbs, 1910, pp. 369-370, 374). Small grabens have also been created in fans by the extension associated with shearing along a strike-slip fault (Dibblee, 1952, p. 39).

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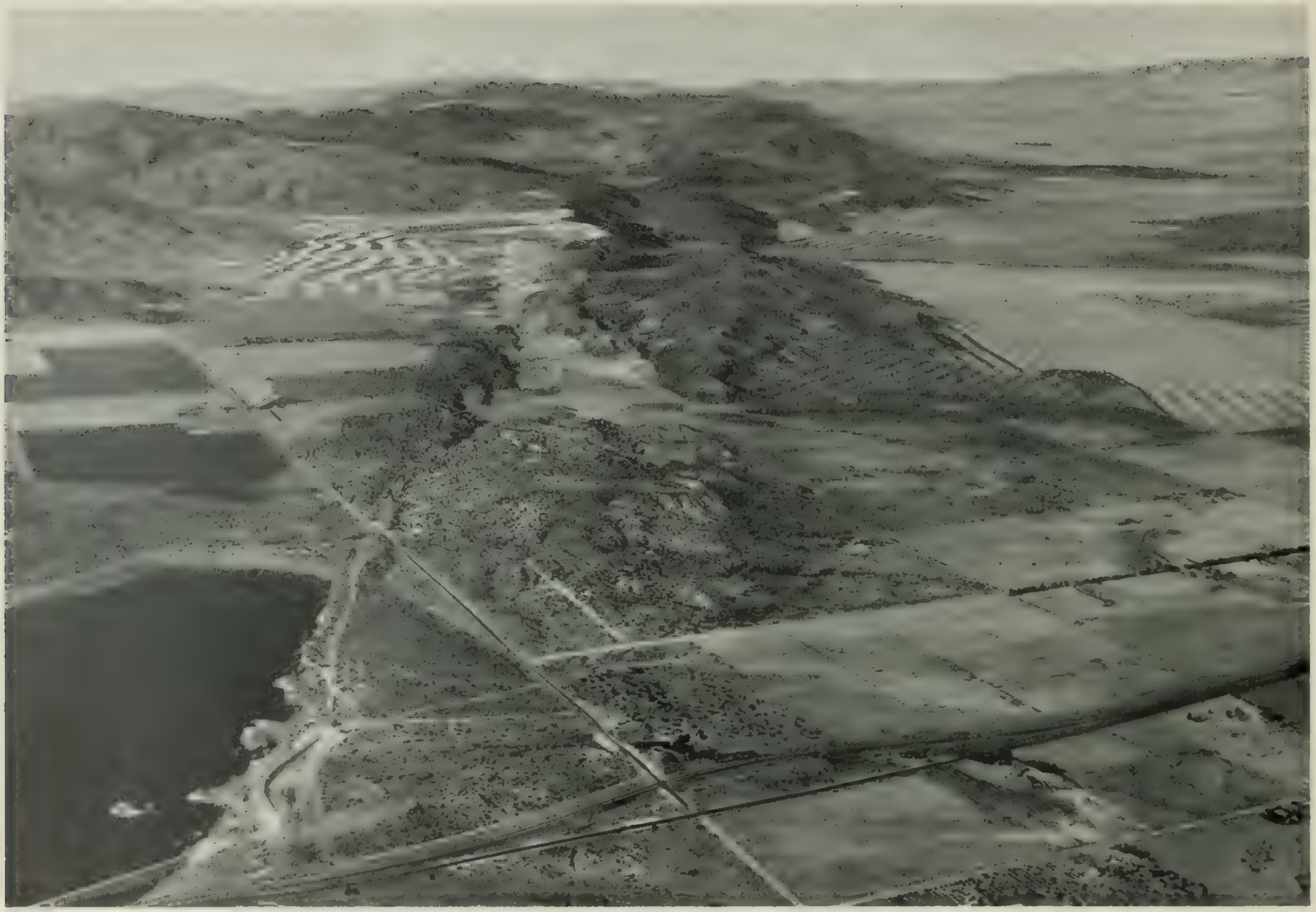

FIGURE 1. View west-northwest along San Andreas fault zone near Palmdale, California. Trace of most active fault lies along right side of Palmdale reservoir. Older fault trace, 0.5 mile to the right, bounds block of Pliocene Anaverde formation which underlies low hills of central foreground. Bend in drainage lines in middle and far distance suggests about 2.5 miles of right lateral displacement on San Andreas fault. Tehachapi Mountains on right skyline contain Garlock fault, which is converging upon the San Andreas fault from the northeast. *Photo by Fairchild Aerial Surveys, Los Angeles.*

A much eroded but still primary product of piedmont faulting is the midfan mesa, an island-like remnant of an old upfaulted fan (Eckis, 1928, pp. 243-246). Although commonly a product of faulting, it need not be exclusively of this origin. A closely allied form is the piedmont bench, consisting of an upfaulted fan or pediment surface at the base of the mountains bounded on its outer side by a piedmont scarplet. Piedmont benches are displayed along the west base of the Panamint Range and along the south sides of the San Gabriel and San Bernardino Ranges.

Fault Rifts. A major and distinctive feature of faulting in southern California is the great rift of the San Andreas (Lawson, et al., 1908, pp. 25-52; Noble, 1927, pp. 26-27; Davis, 1927). It comprises a linear belt of peculiar topographic features which cuts obliquely across the normal topographic grain of the country and is best appreciated as seen from the air. Much of the rift is a shallow trough as much as 6 miles wide, containing various combinations of smaller fault forms, such as slice ridges, sag ponds, shutterridges, offset streams, and other features described in succeeding paragraphs. In some places it is much narrower, consisting simply of one or two deep fault valleys or fault-line valleys with narrow intervening fault-slice ridges, and elsewhere it is simply a broad pass or saddle across a ridge or major divide. If the San Andreas is as old as some of the geologic evidence suggests (Noble, 1932, p. 362; Hill and Dibblee, 1953, pp. 445-449), many of the features in the rift are the product of erosion (Crowell, 1952, p. 22). However, the distinctive topographic details within the rift are largely fault features (Wallace, 1949, pp. 792-795).

Fault-Slice Ridges. These are narrow linear ridges a few feet to a few hundred feet high representing slices of rock squeezed up within a fault zone (Davis, 1927, p. 70). They are also known as pressure ridges (Wallace, 1949, p. 793), and some of the larger ones are bounded by distinct fault branches. Slice ridges are abundant along the San Andreas and other strike-slip faults, and a few have been formed in association with high-angle thrusts, such as the Raymond fault near Santa Anita Park.

Shutterridges. Shutterridges are formed by vertical, lateral, or oblique displacements on faults traversing a ridge-and-canyon topography. The displaced part of a ridge shuts off the adjacent canyon, hence the term (Buwalda, 1937).

Offset Streams. Offset stream channels are a common companion of shutterridges along strike-slip faults and in places lateral displacements of as much as 1.5 miles are thus recorded (Wallace, 1949, pp. 799-800; Hill and Dibblee, 1953, p. 451). Offsets of this magnitude must have been produced by repeated small shifts, with the stream reestablishing the continuity of its course during the intervening periods. The best examples of offset streams are associated with relatively recent displacements and involve shallow gullies, ravines, or small canyons. In the instance of deeper canyons, a distinction between displacement by faulting and diversion by subsequent erosion and capture is not always easily made. Excellent examples of offset streams are found along the San Andreas fault in Carrizo Plains (Wood and Buwalda, 1931) and along the Garlock fault north of Randsburg (Hill and Dibblee, 1953, p. 451). Offset streams also indicate recent strike-slip movement on some of the faults in the Basin Range country (Curry, 1938b; Noble, 1941, p. 960; Hopper, 1947, p. 399; Maxson, 1950, p. 107).

Closed Depressions. Depressions with closure are a common, and in many instances distinctive, product of recent faulting. If small and containing water, they are known as sag ponds, otherwise they may be termed fault-sags (Lawson, et al., 1908, p. 33). These depressions are created chiefly by differential movement between slices and blocks within a fault zone or by warping and tilting associated with differential displacement along a fault. Closure created through damming of fault trenches, troughs, or valleys by deposition is a secondary feature. Closures can also be created by fault displacements which dam normal drainages, or by relative depression of large blocks between separate faults. The basin of Searles Lake may be an example of the former (D. F. Hewett, personal communication).

Fault Valleys. Faulting creates linear depressions of various sizes and characteristics. The largest fault valleys in southern California are grabens, of which Owens Valley is certainly an outstanding example. Another type is the fault-angle valley occupying the depression between a fault scarp and the backslope of a forelying tilted block (Cotton, 1950, p. 748). Panamint Valley appears to be such a feature. Still other valleys are created by relative uplift on opposite sides of two parallel thrust faults, as demonstrated by the central section of Santa Clara Valley, Ventura County, which is bounded on the north and south respectively by the San Cayetano and Oakridge thrusts. The relatively youthful age of sedimentary rocks composing the Santa Clara Valley block and a considerable alluvial fill indicate that this is primarily a fault valley and not a secondary product of erosion. Smaller, narrower valleys are created within major fault zones by relative depression of narrow slices. These features are particularly difficult to distinguish from subsequent fault-line valleys formed by erosion.

Fault Troughs. In size and character fault troughs resemble narrow fault valleys but differ therefrom in not being limited to a

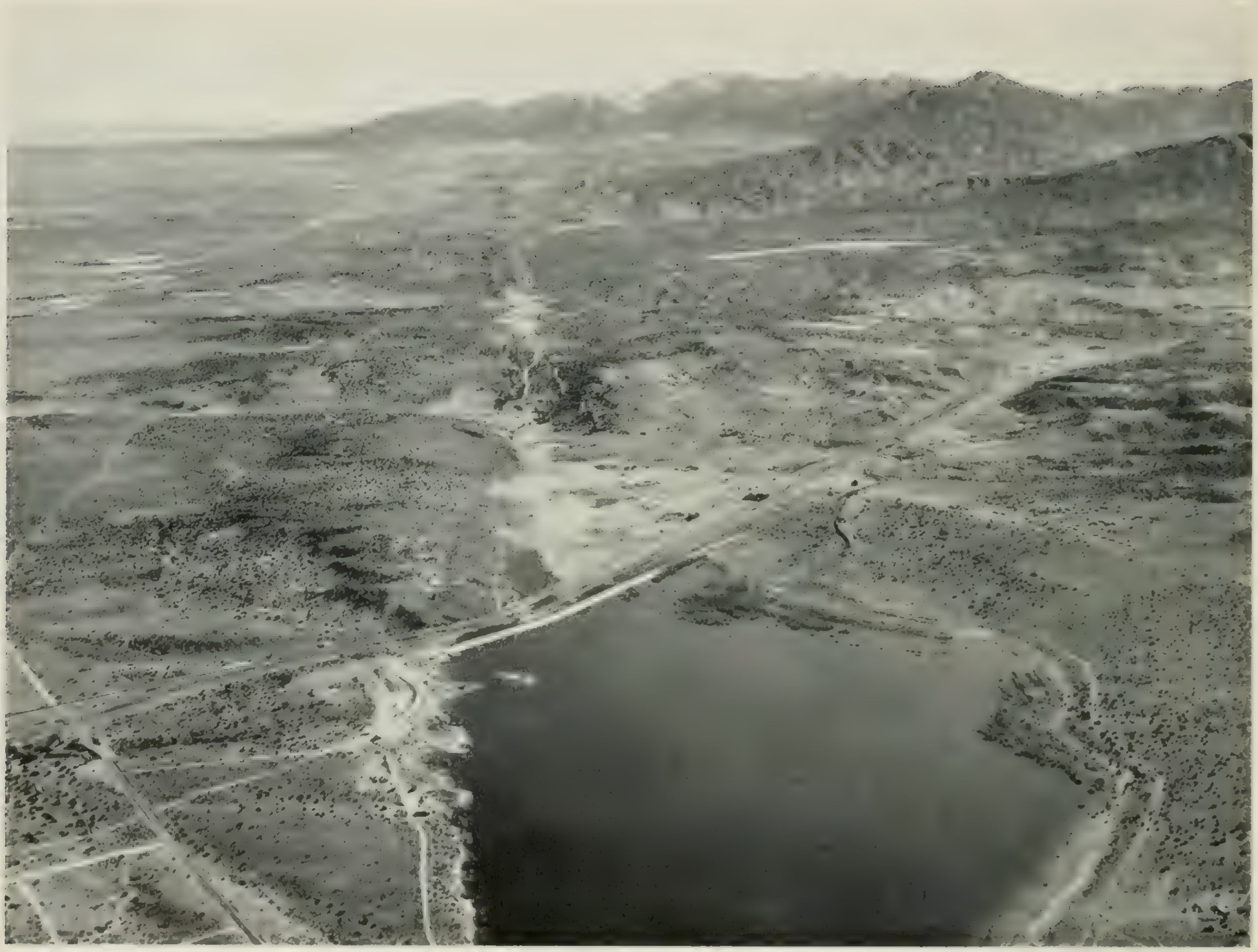

FIGURE 2. View east-southeast along San Andreas fault zone near Palmdale, California. Trace of most active fault extends along left side of Palmdale reservoir, past small sag pond just beyond highway, along the trough beyond, and eventually into the San Gabriel Mountains where it forms broad notch on skyline ridge. *Photo by Fairchild Aerial Surveys, Los Angeles.*

single drainage system. Troughs can cross divides or ridges and may include several fault valleys. Fault troughs constitute major features within rift zones.

Fault Trenches. Trenches or clefts (Davis, 1927, p. 63) are similar to fault troughs but smaller. They form principally within major fault zones and are usually underlain by a fault slice that has been depressed. The moat along the base of a piedmont scarplet in alluvium is a type of trench, and open cracks in the ground formed by lurching associated with recent earthquakes have also been called fault trenches.

Kernbuts and Kernrols. These forms were originally defined by Lawson (1904, pp. 331-343) as primary features created by displacement on a fault traversing a hill slope in such a manner that a projecting ridge or buttress, the kernbut, and an intervening depression or fosse, the kerncol, are formed. The type locality has since been shown to be one of fault-line forms (Webb, 1936, p. 636), but this does not destroy the validity of Lawson's original concepts, and his terms should be retained for the corresponding primary features (Lahee, 1952, p. 317). The forms related to Cotton's cicatrice (1950, p. 753) are closely similar if not identical in some instances. Fault benches (Lahee, 1952, p. 316) are also created by hillside faulting. The outer edge of a bench may be a kernbut but the kerncol is lacking.

Fault Gaps. A fault gap is formed by a displacement that laterally offsets a ridge so that the two parts are no longer continuous (Lahee, 1952, p. 336). Small gaps of this nature are fairly common along the larger strike-slip faults with recent displacement. Some of the major passes leading into the southern California coastal region may be at least partly of this nature.

Fault Saddles. These are notches, cols, or saddles in ridges created by actual displacement of the ridge crest by faulting. They are much less common than fault-line saddles and might well be treated as a particular type of kerncol.

Ground Features. Various types of open cracks, furrows, and small ridges are created in the ground by lurching and other movements associated with earthquakes. These features are all geologically short-lived, and many of them do not appear to represent the actual displacement on the fault plane (Buwalda and St. Amand, 1952, pp. 4-5). One of the more striking of these forms is a small ridge 1 to 2 feet high, known as a mole track, formed by humping up and cracking of the ground.

Knick Points. Some streams crossing active faults display a sudden steepening of gradient. Such knick points may have migrated upstream from the fault, but if their relief is the product of actual fault displacement they should be treated as primary features. It would of course also be possible to have a fault-line knick point produced by differential erosion of hard and soft rock brought into juxtaposition by faulting. Streams within the Panamint Range display steepened profiles attributed to movement on the boundary fault (Maxson, 1950, pp. 108-112).

Folds. The principal surface expression of buried faults may be folds of one type or another. The belt of en echelon folds constituting the Newport-Inglewood uplift has been attributed to forces associated with strike-slip displacement on the Inglewood fault (Reed and Hollister, 1936, pp. 125-133). L. F. Noble (personal communication) is also inclined to relate small en echelon folds on the floor of Death Valley to lateral fault displacements.

SECONDARY FAULT FEATURES

Fault-Line Scarps. The principal secondary fault feature is the fault-line scarp, a form created wholly by erosion acting upon rock units of different resistance juxtaposed by faulting. The relief between top and bottom of a fault-line scarp is due solely to erosion. It may be the product of first-cycle erosion, without an intervening episode of planation, or of second-cycle erosion following planation. The fault-line nature of scarps facing in opposite direction to the original fault scarp is more easily established than of scarps facing in the same direction (Blackwelder, 1928). Broad geomorphological and geological relations are of help in this connection (Cotton, 1950, pp. 719-721), and on such a basis a number of fault-line scarps can probably be shown to exist within the Transverse Ranges (Putnam, 1942, p. 751).

Composite scarps on which the relief is due partly to fault displacement and partly to erosion may be even more common. In places, the south face of the San Bernardino Mountains near Beaumont and Banning is a composite scarp.

Fault-Line Valleys. Fault-line valleys are developed by erosion in the soft crushed material along fault zones and are abundant in this region. Many fault-line valleys are undoubtedly formed by headward erosion and are subsequent in the purest sense, but there is no reason why they must all be of this origin as inferred by Cotton (1952, p. 182). Probably, a number of fault-line valleys in southern California originated as consequent stream courses along fault depressions which have since been transformed to fault-line valleys by erosion. Many, of course, are composite, the present valleys being created partly by faulting and partly by erosion. The east and west forks of San Gabriel River look like good examples of subsequent fault-line valleys

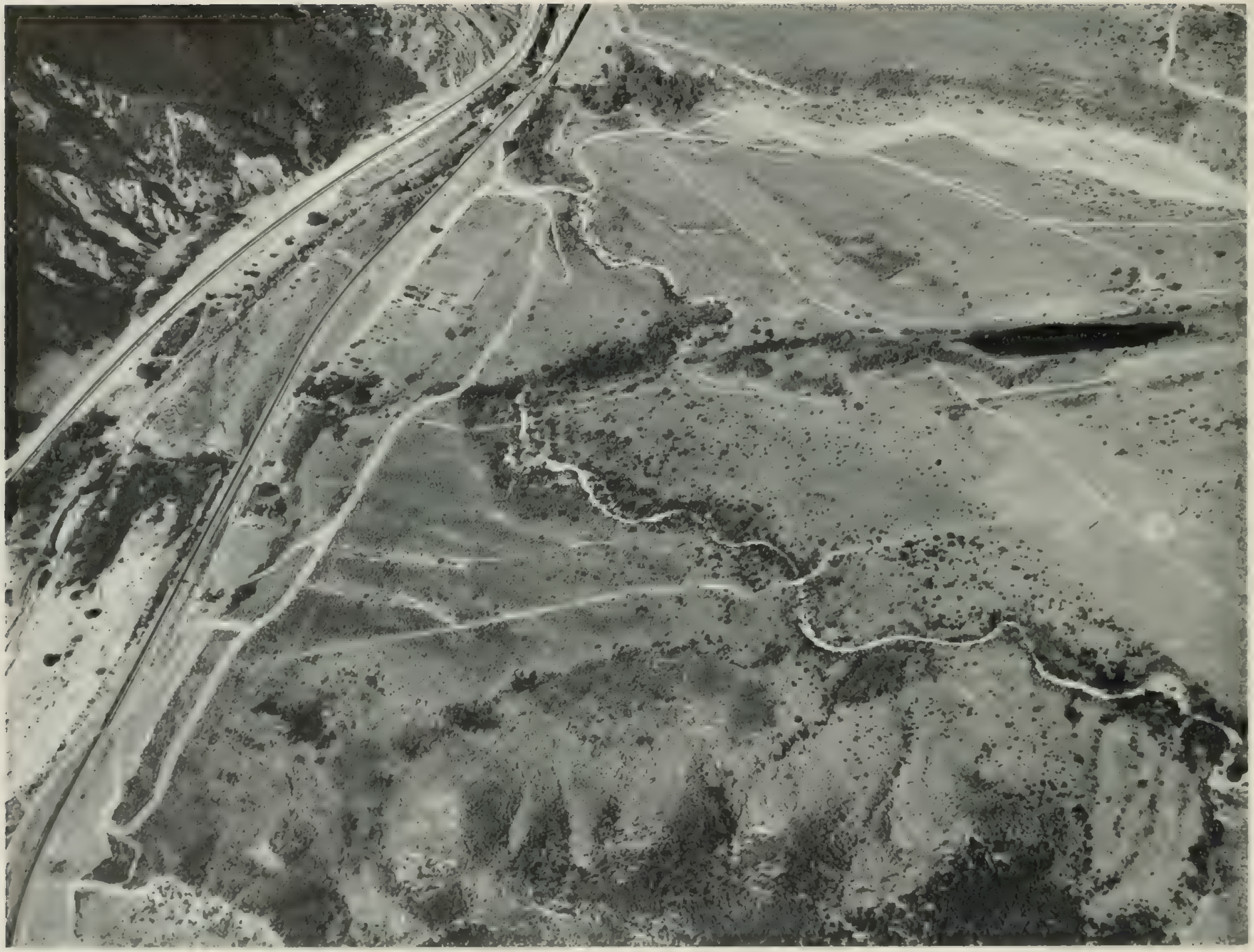

FIGURE 3. View south across active trace of San Andreas fault in Cajon Pass. Note sag pond at right, offset stream in center showing right-lateral displacement, and change of vegetation at fault trace crossing Cajon Wash, indicating a difference in ground-water conditions on opposite sides of the fault. *Air photo by J. S. Shelton and R. C. Frampton.*

developed by headward erosion. Many valleys along the San Andreas rift, such as Lone Pine Canyon and Swartout Valley, are possibly of fault-line origin, although more study is needed to establish this point and to determine whether they are consequent or subsequent. Mill and Mission Creeks in the San Bernardino Range come in the same category, and at least part of the Kern River Canyon in the southern Sierra Nevada has been shown to be a fault-line feature (Webb, 1936, p. 636).

Evidences of stream capture can be useful in establishing the subsequent nature of some fault-line valleys, and care must be exercised in deeply dissected areas to avoid mistaking diversion of streams by capture for displacement by faulting.

Fault-Line Gaps. Fault-line gaps resemble fault gaps but are formed solely by erosion of resistant ridge-making units laterally offset by earlier faulting. Small fault-line gaps are relatively numerous in parts of the Transverse Ranges displaying fault-line features. Many of the larger gaps in southern California created by faulting are possibly composite forms in which the initial relief of the original fault gap has been increased by deepening through erosion, as demonstrated by the course of Cajon Creek along the San Andreas fault between the San Gabriel and San Bernardino Mountains (Noble, 1927, p. 33).

Fault-Line Saddles. Fault-line saddles are created by more rapid erosion of ridge crests where crossed by faults. They are one of the most sensitive indicators of ancient fault lines that lack almost all other forms of topographic expression. Good examples of fault-line saddles can be seen along the San Gabriel fault within the San Gabriel Range.

Drainage Rejuvenation. Dissection resulting from fault displacement is a secondary product which cannot always be satisfactorily interpreted because of its possible polygenetic origin. However, careful work can show in some instances that interruptions of stream cycles expressed in the form of dissected terraces and entrenched open-valley forms are due to faulting. Terraces in the San Gabriel Mountains are graded to piedmont benches along the south face of the range which have been uplifted by faulting (Muehlberger, 1950, p. 14).

Depositional Forms. Deposition creates a host of secondary topographic features along fault scarps and to a lesser extent along fault-line scarps. Alluvial cones, fans, and aprons along the bases of fault scarps are common in southern California and attain spectacular development in the desert country, particularly in Owens, Panamint, and Death Valleys.

Various products of mass movements are locally associated with fault scarps, the most distinctive being landslides and rock falls. An exceptionally fine example of a rock fall derived from a fault scarp can be seen at Blackhawk Canyon on the north side of the San Bernardino Mountains (Woodford and Harriss, 1928, pp. 287-289).

Topographic Fault-Line Outliers. Low-angle thrust faults have been described from a considerable area in the eastern Mojave Desert and the southeastern Basin Range country (Hewett, 1928; Noble, 1941; Kupfer, 1953). Erosion of these low-angle thrust masses has left a number of isolated hillocks and ridges capped by remnants of the thrust plates. Good examples are found in the Shadow Mountains, Silurian Hills, Ibex Hills, and the Jubilee Pass area. These are strictly secondary fault-line forms created by erosion which owe their special character to the more resistant capping of the thrust plate.

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4. BEACH AND NEARSHORE PROCESSES ALONG THE SOUTHERN CALIFORNIA COAST[*]

By Douglas L. Inman[†]

Erosional and depositional nearshore processes have played an important role in determining the configuration of the southern California coastline. Erosion is usually dominant off headlands and along coastal sections backed by cliffs of alluvium and other unconsolidated material, whereas deposition is most common along indentations between headlands. The over-all effect of such processes is usually a straightening and smoothing of the coastline. However, this is not always the case; differential wave erosion may cause more rapid erosion of material between headlands and thus cause irregularities in the coastline.

The predominance of deposition or erosion in any particular place depends upon a number of interrelated factors such as the amount of available beach sand and the location of its source, the configuration of the coastline and of the adjoining ocean floor, and the effects of wave, current, and tidal action (fig. 1). The establishment and persistence of natural sand beaches and related phenomena are often the result of a delicate balance among a number of these factors, and any changes, natural or man-made, tend to upset this equilibrium.

Source of Beach Sediment. The principal sources of beach and nearshore sediment along the southern California coast are the streams which periodically bring large quantities of sand directly to the ocean, and the sea cliffs of unconsolidated material which are being eroded by waves. In some isolated instances sediment may be supplied by erosion of older unconsolidated deposits in shallow offshore areas. Shepard and Grant (1947) found that the wave erosion of rocky coasts in southern California has been negligible during the past 50 years, even where the rocks were relatively soft shales. On the other hand, they found a retreat of as much as a foot a year in unconsolidated formations.

Streams, however, are by far the most important source of sand. The shoreline at the mouth of the Santa Clara River, near the city of Ventura, advanced 300 feet between 1933 and 1938 principally as a result of deposition during the 1938 flood. The Corps of Engineers (1952) estimate that the average rate of littoral drift of sand from the Santa Clara River delta, toward Port Hueneme to the southeast, was about 800,000 cubic yards a year. The combination of abundant local source of sand and protection from wave erosion by the Channel Islands and Point Conception has resulted in building the shoreline along this section of coast well seaward of the adjacent headlands of Ventura and Point Mugu.

Beaches do not always have local sources of sand, but may receive sand from other beaches many miles away. For example, there is evidence (Trask, 1952) that the beaches near Santa Barbara, where the average littoral drift is about 280,000 cubic yards a year, may receive some sand from beaches north of Point Conception. Also, studies of the beaches in the Santa Monica area suggest that some of the sand there is derived from sources northwest of Point Dume and possibly from northwest of Point Mugu (Handin, 1951, p. 42).

Southern California beaches are generally narrow and backed by sea cliffs except where deposition has caused the beaches to build seaward. Examples of wide beaches are found near the Santa Clara River, along portions of Santa Monica Bay, at Newport Beach, and at Mission and Silverstrand Beaches near San Diego. The beach material consists predominantly of well sorted medium to fine sand, interrupted here and there by pebble and cobble foreshores. The coarsest material is commonly found on pocket beaches near rocky headlands, as at Point Mugu and Point La Jolla. The composition of the beach sands is mostly quartz with minor amounts of the feldspars and heavy minerals. The heavy minerals (i.e., those with a specific gravity greater than about 2.85) generally comprise between 1 and 15 percent of the total sample, and are most abundant in the finer size fractions. The most common heavy minerals are hornblende, augite, epidote, magnetite, ilmenite, apatite, garnet, sphene, and zircon (Handin, 1951; Inman, 1950b, 1953; Trask, 1952). Biotite is common in the stream sands and offshore sediments, but because it is easily retained in suspension, is usually rare in the beach sands.

Waves. Waves and the currents which they generate are perhaps the single most important factor in the transportation and deposition of nearshore sediments. Waves are effective in moving material along the bottom, in placing it in suspension for weaker currents to transport, and, in the absence of beaches, waves erode cliffs and sea walls directly by the force of their breaking. The deciding factors in determining the effect of waves on the coastline, and the direction of the wave-generated longshore currents which move material along the coast are: (1) the direction of approach of the waves, (2) the wave characteristics, such as height and length, and (3) the configuration of the sea floor.

Wave action along the southern California coast is seasonal in nature, in response to the changing wind systems over the Pacific Ocean where the waves are generated. Important meteorological con-

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[*] Contribution from the Scripps Institution of Oceanography, New Series No. 657. This summary has been compiled as part of a program of investigation supported by the Beach Erosion Board, Corps of Engineers, under contract with the University of California.

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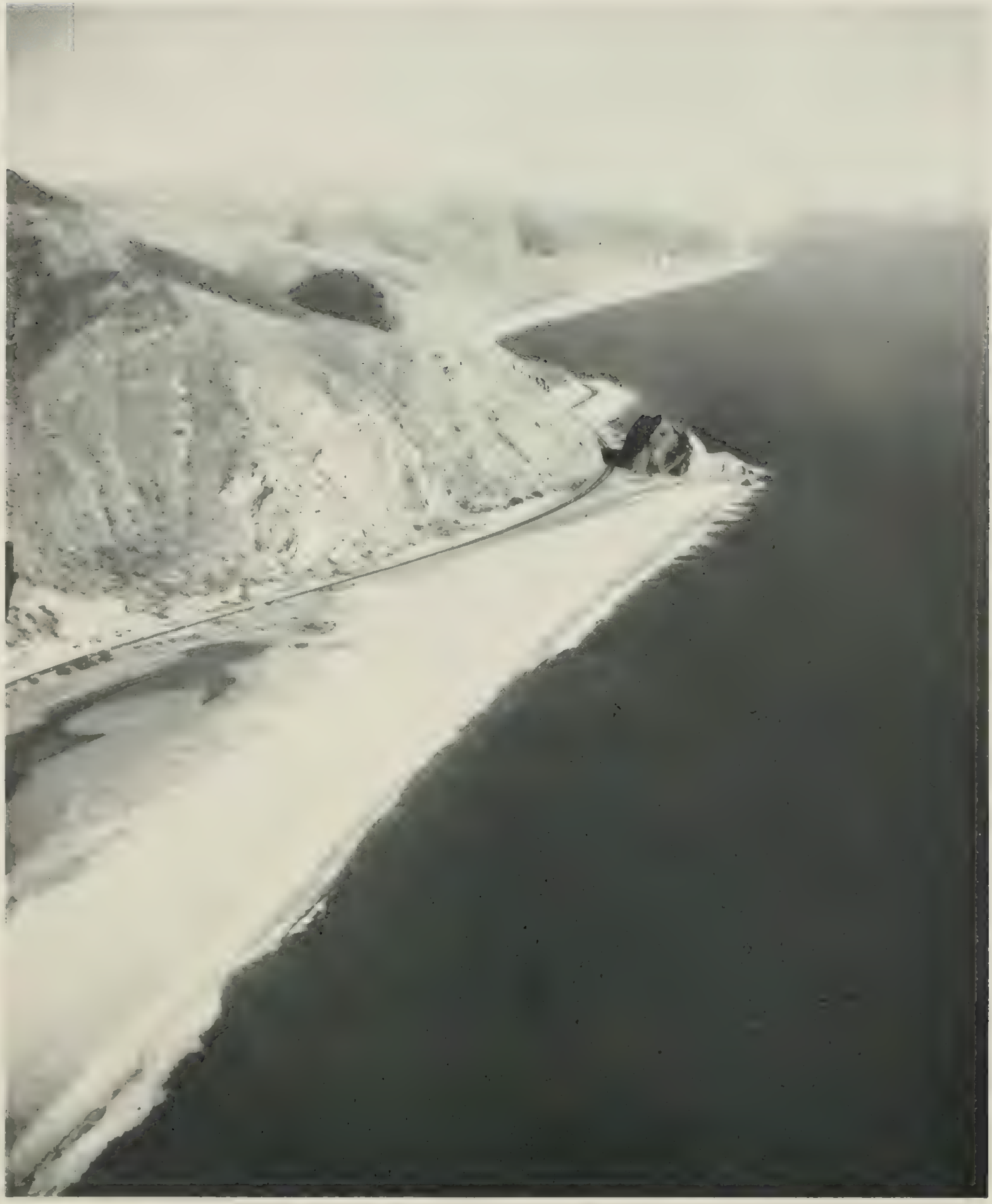

FIGURE 1. The effect of headlands on the accretion of beach sand is shown in this photograph of Point Mugu, California (view southeast). The point forms a natural obstruction which interrupts the littoral drift of sand, causing accretion and a wide beach to form on the up-current side (foreground), and cliff erosion with occasional pocket beaches in the current lee where the supply of sand is diminished. *Photo courtesy Department of Engineering, University of California, Berkeley.*

ditions resulting in high waves along the coast are local storms, coastal fronts, and storms in the Gulf of Alaska. These waves occur mostly during the winter and spring and occasionally in the fall, and approach the coast principally from the northwest and west (Scripps Institution of Oceanography, 1947). During the summer months the waves are characteristically much lower in height and approach the coast from the west and south-southwest. The most southerly of these waves, sometimes called "southern swell," are generated during our summers by winter storms in the southern hemisphere and may travel more than 5,000 miles before breaking on the shore of southern California.

The profiles of ocean swell in deep water are long and low, approaching a sinusoidal form. However, as waves enter shallow water the wave velocity and length decrease, the wave steepens and the wave height increases until the wave train consists of peaked crests separated by flat troughs. Near the breaker zone the process of steepening is accelerated so that the breaking wave may attain a height several times greater than the deep-water wave. This transformation is particularly pronounced for long-period swell from a distant storm. The profiles of local storm waves show considerable steepness even in deep water, so that the shallow-water steepening is not as pronounced as in the case of ocean swell (Munk and Taylor, 1947).

The shallow-water transformation of waves commences at the depth where the waves feel bottom. This depth is equal to one-half the deep-water wave length, where the wave length is the horizontal distance from wave crest to crest. The deep-water wave length in feet is given by the relationship $L = 5.12T^2$, where T is the wave period in seconds. Upon entering shallow water waves are also subjected to refraction, a process in which the wave crests tend to parallel the depth contours. For straight coasts with parallel contours, this decreases the angle between the approaching wave and the coast, and causes a spreading of the energy along the crests. The wave height is decreased by this process, but the effect is uniform along the coast. A submarine canyon or depression causes waves to be refracted or bent in such a manner that waves over the canyon will diverge, causing the waves to decrease in height and the line of wave crests to be convex toward the shore. Waves will converge on either side of the canyon or over a ridge, causing the wave height to increase and the line of wave crests to be concave toward the shore. The amount of wave refraction and consequent change in wave height and direction at any point along the coast is a function of wave period, direction of approach, and the configuration of the bottom topography.

Waves from distant storms, such as southern swell, may have periods as great as 20 seconds or more when they reach the southern California coast. Since refraction commences when waves reach a depth equal to one-half the wave length, waves with periods of 20 seconds will feel bottom and be refracted by topographic features on the ocean floor in depths as great as 1000 feet. Thus the formation of beaches and the effect of waves on a coastline may be influenced by the topography of the bottom many miles from the coast. The concentration of wave energy at points along the coast by submarine ridges often results in severe erosion and damage to coastal structures. Damage from this cause occurs periodically along the California coast when the wave period, deep-water direction of approach, and height are such as to focus energy on coastal structures (Horrer, 1950; Inman, 1950a).

Currents. When waves break so that there is an angle between the crest of the breaking wave and the beach, the momentum of the breaking wave has a component along the beach in the direction of wave propagation. This results in the generation of longshore currents that flow parallel to the beach inside of the breaker zone (fig. 2). These currents are largely responsible for the littoral drift of beach material. After flowing parallel to the beach as longshore currents, the water is returned seaward along relatively narrow zones by rip currents. The net onshore transport of water by wave action in the breaker zone, the lateral transport inside of the breaker zone by longshore currents, and the seaward return of the flow through the surf zone by rip currents constitute a near-shore circulation system. The pattern that results from this circulation commonly takes the form of an eddy or cell with a vertical axis.

In many cases where waves break along a straight beach with parallel bottom contours, it is possible to predict the velocity of the longshore current from a consideration of wave and beach characteristics (Inman and Quinn, 1952). However, where the beaches are not straight, or where offshore topography causes differential wave refraction, the longshore currents are dependent on the gradient of breaker height along the beach as well as on the angle between the breaking wave and the beach. For such cases, the positions of the circulation cells are largely dependent upon the location of zones of wave convergence and divergence, and quantitative prediction of longshore velocity cannot be made (Shepard and Inman, 1951a).

Points, breakwaters, and piers all influence the circulation pattern and alter the direction of the currents flowing along the shore. In general these obstructions determine the position of one side of the circulation cell. In places where relatively straight beaches are terminated on the down-current side by points or other obstructions, a pronounced rip current extends seaward. During periods of large waves having strong diagonal approach these rips can be traced seaward for one or more miles.

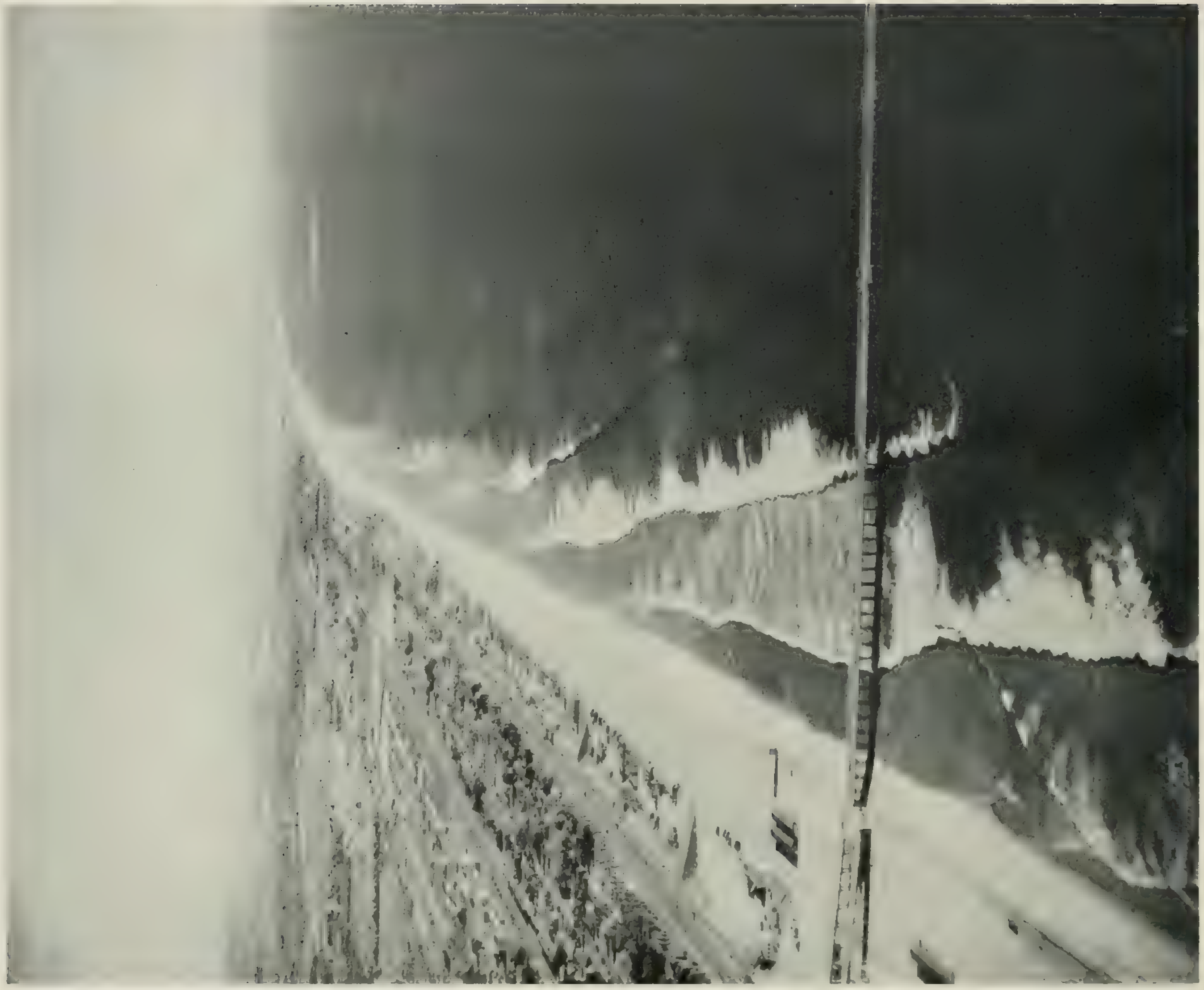

Figure 2. Longshore currents are generated when waves approach the beach at an angle. Such currents flow parallel to the beach and result in a littoral drift of sand along the beach. In this photograph of Oceanside, California, the longshore current is flowing towards the observer. *Photo courtesy Department of Engineering, University of California, Berkeley.*

Longshore currents are largely responsible for the littoral drift of beach material along the coast. Although there are local and temporary reversals of current direction, the net sand transport along most southern California beaches is from the northwest toward the southeast. Obstructions—natural or man-made—in the path of these currents often have profound effects upon the beaches in the neighboring areas. Usually the beaches build seaward up-current from obstructions and are eroded in the current lee, where the supply of sand is diminished (fig. 1). Numerous examples of the effectiveness of coastal structures in interrupting the littoral drift of beach material are found along the California coast, particularly where breakwaters and jetties have been constructed as at Santa Barbara, Port Hueneme, Santa Monica, and Redondo Beach. The rate of accretion of sand behind such structures has provided the most reliable information about the rate of littoral drift of sand along the coast.

Mechanics of Beach Formation. Waves are effective in causing sand to be transported laterally along the beach by longshore currents, and in causing movements of sand from the beach foreshore to deeper water and back again to the foreshore. Along the southern California coast the migration of sand between the beaches and deeper water is seasonal, in response to the changes in wave height, period, and direction of approach. In general, the beaches build seaward during the small waves of summer and are cut back by high winter storm waves (Shepard and La Fond, 1940; Shepard, 1950). There are shorter cycles of cut and fill associated with spring and neap tides, and with non-seasonal waves and storms. Bottom surveys indicate that most offshore-onshore interchange of sand occurs in depths less than 30 feet, but that some effects may extend to greater depths (Shepard and Inman, 1951b).

The mechanics of transportation of beach and nearshore material are not clearly understood. However, there has been much research on the problem, and a summary of available concepts based partly on theory and partly on observations is given in the following discussion (also, see Eaton, 1951).

As mentioned in the discussion of longshore currents, there is a shoreward mass transport of water associated with wave motion near the breaker zone. This shoreward transport of water can apparently be interpreted as resulting in a rise in the sea surface near shore. The piling up of water must be compensated by a seaward return flow, part of which is in the form of rip currents. Application of solitary wave theory to the surf zone (Munk, 1949a), supported by field observations (Inman and Quinn, 1952), suggests that the shoreward mass transport of water is a maximum at the water surface and that, in addition to rip currents, this transport is compensated by a net seaward return flow along the bottom. The magnitude of net offshore drift along the bottom (as determined from averages over straight beaches three-quarters of a mile long and for periods of one hour) usually does not exceed three-tenths of a foot per second.

The instantaneous particle motion associated with shallow-water progressive waves is oscillatory in nature, the motion under the crest being in the direction of wave propagation, while that under the wave trough is in the opposite direction. As waves near the breaker zone, a differential develops between the magnitude of the crest and trough orbital velocities; the velocity under the crest exceeds that of the trough and becomes of shorter duration. In general, the differential between crest and trough orbital velocities increases as the wave height and frequency decrease. However, the picture of wave motion in shallow water is considerably complicated by currents and by longer-period waves or surges which in some cases may result from the alternation of groups of high and low waves in the surf zone (Munk, 1949b; Williams and Isaacs, 1952).

The relative increase in the onshore velocity under the wave crest as compared with the offshore velocity of the wave trough probably accounts for the shoreward migration of sand during periods of low waves, particularly when the waves have long periods. On the other hand, a greater amount of material is maintained in suspension above the bottom when the waves are high and have short periods, and for this condition, the differential between onshore and offshore orbital velocities is much less. Thus the net offshore drift along the bottom may result in a net offshore transport of material when the waves are high and have short periods. It is also possible that a net transport of sediment could exist in the absence of a net current if a horizontal gradient were to develop in the concentration of suspended material. Such a gradient does exist near the surf zone (Beach Erosion Board, 1933), where the concentration of suspended material is greater in the zone of breaking waves than it is seaward, and may result in an offshore transportation by diffusion.

High waves also augment beach erosion by increasing the velocity of the currents in the nearshore circulation system. Sand is transported laterally along the beach by longshore currents and through the breaker zone to deeper water by rip currents.

Grant (1948) points out that the mechanics of accretion and erosion of the beach foreshore appear to be connected with the height of the water table in the beach, which in turn is related to waves and tides. Percolation of the uprush into a dry beach reduces the amount of flow in the backwash and is thus conducive to deposition of the sand transported by the uprush. Large waves elevate the water table in the beach. When the beach is saturated the backwash has a higher velocity which enhances erosion of the foreshore.

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5. PLEISTOCENE LAKES AND DRAINAGE IN THE MOJAVE REGION, SOUTHERN CALIFORNIA

By Eliot Blackwelder *

During Pleistocene times the southwestern states experienced at least four epochs of cold climate, lasting thousands of years each and alternating with much longer warm epochs. Regardless of any changes in the rainfall, the cold epochs doubtless had a moister climate, because of the lower rate of evaporation. On the same principle, the warm inter-glacial epochs must have been relatively dry. Evidence for the more recent climatic episodes is relatively abundant and well preserved, and hence their history is better known than that of the older ones. In order of increasing age, the cold epochs in the Sierra Nevada and adjacent areas have been termed Tioga, Tahoe, Sherwin, and McGee (Blackwelder, 1931).

In a typical age of cold climate, such as the Tioga, the snowline descended to an altitude of about 6,000 feet in the Sierra Nevada and other high ranges. Glaciers formed on the highest mountains and crept downward to altitudes as low as 4,000 feet. Mountain streams no longer disappeared into the gravelly deposits along the bases of the mountains, but extended out into the undrained hollows until they filled many of them to overflowing. Thus lakes were formed in such basins as Owens and Inyokern, and the excess of water, spilling over from one basin into the next, seems to have reached the Colorado River in at least one of the earlier ages. By this process there came into existence the chain of lakes and rivers shown on the sketch map (fig. 1).

In the same times of cold climate, the life-zones migrated downward and also generally southward. The Alpine zone of treeless tundra and midyear snow-banks descended to about 6,000 feet, while the lower edge of the forest belt covered the lower slopes of the mountains down to an elevation of about 2,500 feet above sea level. The Mojave Desert lowlands probably looked like the plateau of northern Nevada today, with its sage- and grass-covered plains and its hills dotted with cedar and pinyon trees. The typical desert was crowded far southward.

Most of the lakes were probably fresh, excepting those which did not overflow. Fishes of several kinds migrated up from the Colorado River; and a few of their descendents still survive in the lakes and creeks of the higher mountains. In rare instances they now occur in springs even in the bottoms of some of the most arid basins.

The geologic record of the last two glacial episodes (Tahoe and Tioga) is fairly clear, whereas that for the earlier glacial ages is scanty and obscure. The lakes of probable Tioga age have left almost continuous wave-cut terraces, as well as gravel bars and spits. Their bottom deposits are in most places still concealed beneath the surface layers, although locally, as in the narrows of the Mojave River, they have been deeply trenched and are therefore well exposed. Erosion, particularly by desert floods, has erased nearly all traces of shoreline features of the lakes that probably existed in the Sherwin and earlier glacial ages. Some of the deeply eroded lake-beds along the Amargosa River may well be of that age, and it seems probable that others will be found buried in the central portions of those basins that have not been dissected.

Owens River. Owens River, the largest stream of the Mojave Desert, drew its water supply mainly from rain and the melting snows in the high Sierra Nevada. Its upper tributaries have cut notches in the glacial moraines, flood-plains, and terraces farther downstream. This influx of water during the cold epochs soon filled the relatively shallow basin (about 100 feet in maximum depth) south of Lone Pine, and thus formed the ancestors of Owens Lake. Overflowing the southern rim of the basin, the river soon cut a spacious trench in the Pleistocene lava flow below Little Lake (fig. 2). At the upper end of this trench are an interesting box gorge and a dry waterfall, and many large potholes in the basalt.

Emerging into the broad Indian Wells basin, the river formed a shallow lake (35 feet) whose site is now marked by the China Lake salina. This in turn overflowed into the much lower Searles basin to the east. The outlet stream cut the usual notch across the ridge on the east side of the Inyokern basin; unfortunately, this feature is no longer readily accessible, because it is included in the U. S. Naval Reservation.

In the Searles basin the river formed a lake, which was about 16 miles long and more than 375 feet deep, during the latest of the cold, moist epochs. At that stage the basin was the final sink of Owens River, and its only outlet was through evaporation. The lake therefore became saline, as is now attested by the thick deposits of complex salts which occupy a large area in the center of the basin. On both the east and west sides of the Searles basin the wave-eroded shore terraces are still nearly continuous and easily recognized. On the north and south sides, where the gradient of the preceding surface was too gentle to permit erosion by the waves, the ancient shores are marked chiefly by extensive gravel bars. On one of the latter, on the southwest side of the old lake, there is a remarkable cluster of massive tufa monuments or towers, some of which are nearly 100 feet high and are still well preserved (fig. 3).

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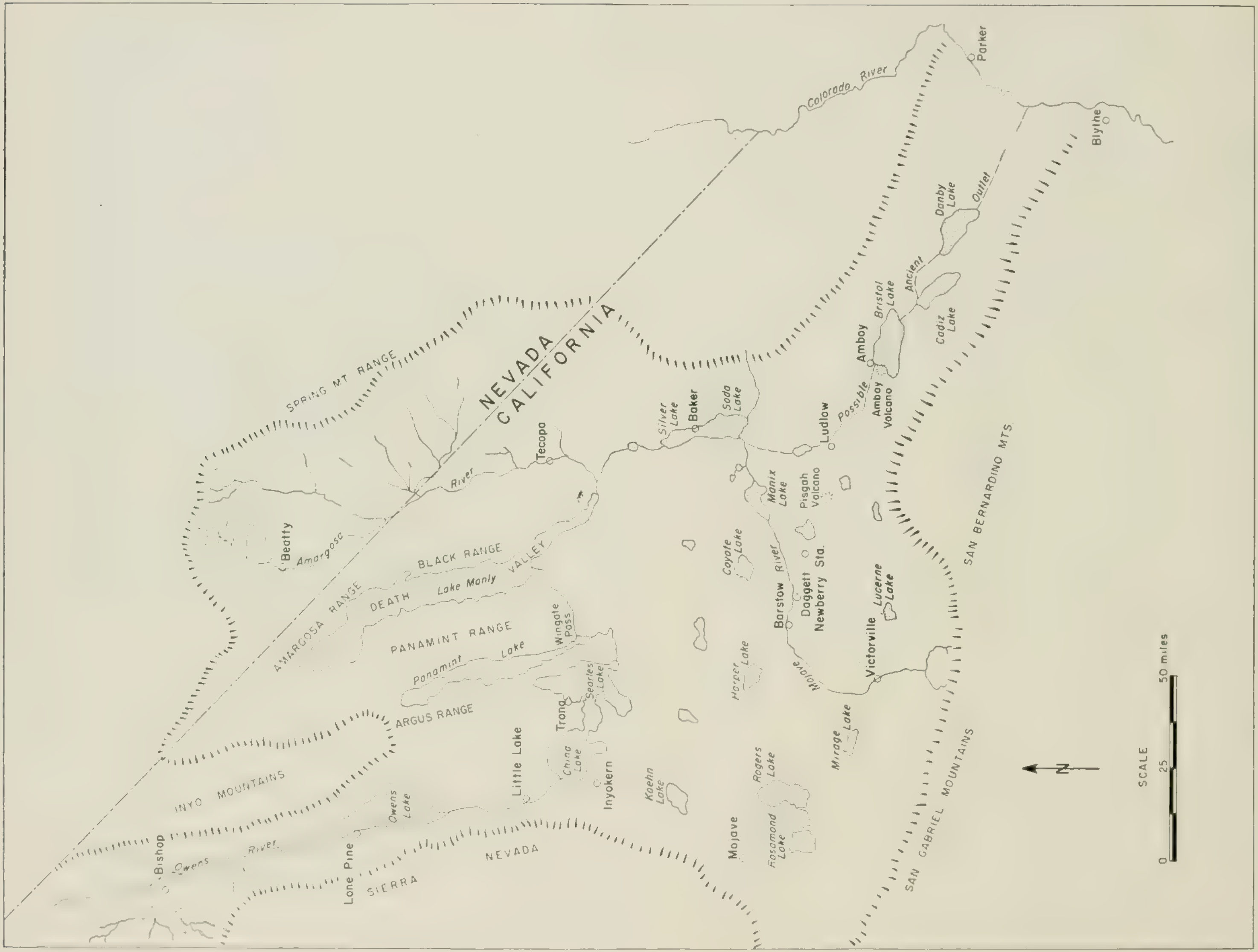

FIGURE 1. Map of the Mojave region and adjacent areas, showing lakes and drainage during a part of Pleistocene time (probably the Tahoe age).

In a somewhat earlier cold time, presumably the Tahoe age, Searles Lake was more than 640 feet deep, and overflowed across a broad pediment on the southeast side of the basin, finding its way eventually east and northward into Panamint Valley. On the west the lake overflowed the low divide at the head of South Wells Canyon and joined the much shallower lake in Indian Wells Valley. Because of the overflow to the southeast the older Searles Lake must have been fresh, although it doubtless became saline in the course of its decline, as the climate became warmer and drier. Some of the buried salt beds, which have been revealed by drilling, may represent this episode. The shore terraces of that age are discontinuous and generally obscure. They are best seen, when the light is favorable, on the projecting shoulder east-southeast of Trona. Several rows of dilapidated tufa towers of this age may still be recognized on the slopes of Salt Wells Valley, west of Searles Lake, at elevations of 2,200 to 2,260 feet above sea level.

While it is reasonable to infer that the basin was occupied by lakes in still earlier cold epochs, no evidence for their existence has thus far been recognized. Their deeply buried deposits may some day reveal part of the story.

Augmented by creeks from the Panamint and adjacent ranges, the ancestral Owens River made lakes in the long and deep trough known as Panamint Valley. The lake, probably of Tahoe age, was about 62 miles long and more than 920 feet deep. Nearly all traces of its shore features have been destroyed by erosion, but remnants of shore terraces may still be seen in a favorable light just south of Ballarat, and a scanty deposit of calcareous sand and tufa is present at an altitude of 1,980 feet along the old wagon road east of the pass at the north end of Searles basin. This lake overflowed through Wingate Pass into Death Valley, and thus also must have been fresh. Desert erosion has, however, removed almost all traces of the erosional features made by the outlet stream.

In the later (Tioga) age, the central part of the Panamint Valley appears to have had a smaller lake less than 200 feet deep, which must have been supplied by creeks from the mountains on either side. It was probably saline. While its shore-lines are obscure, the deposits made in it are now slightly dissected and thus visible, especially west and south of Ballarat. At the same time there must have been a shallow lake in the north end of the Panamint trough and one or more small ones near the southern end, as indicated by the existing playas.

Death Valley, being the lowest of all the basins in the region, probably held lakes during all of the cold ages of the Pleistocene. In addition to the contribution of streams from the nearby ranges, it received water during the earlier epochs from the Owens River system on the west, the Mojave River on the south, and the Amargosa River on the east. At present only the waters of the Amargosa River ever reach the bottom of Death Valley, and then only during exceptional floods.

During a late age (probably the Tioga), Death Valley appears to have contained a lake about 400 feet deep and about 100 miles long. Although its shore features have been recognized in but a few places, there are some well preserved gravel bars, spits, shore terraces and small quantities of tufa (fig. 4). As it dried up, this lake deposited the layer of salt that now forms the bottom of Death Valley in an area about 28 miles long.

In what is presumed to have been the Tahoe age, the larger and better known Lake Manly occupied the main part of Death Valley. This lake must have been at least 600 feet deep, and there is no reason to believe that it overflowed from the valley. Fed by all three of the river systems, the lake must have been about 116 miles long and as much as 10 or 12 miles wide. Well-preserved shore terraces are easily recognized on the slope of a basalt hill near the mouth of Wingate Wash, in the southern part of Death Valley, as well as in areas farther north (fig. 5). Dissected lake deposits of this age are visible a few miles west of Surveyor's Well and in several other localities farther south. Some of the salt-bearing clays which have been revealed by borings in the bottom of the valley may also be of this age.

It is inherently probable that Death Valley contained large lakes during the earlier McGee and Sherwin ages of the Pleistocene. The extensive deposits of calcareous lake clays, a few miles north of the Ubehebe craters, have been so deeply eroded as to suggest that they are of Sherwin age. Whether the associated great lake had an outlet is still problematical. Careful scrutiny of airplane photographs, and of critical localities on the ground, have revealed no traces of shore terraces or outlet notches. However, the fishes that now inhabit some of the springs and small streams in the Death Valley region have their closest affinities with those in the Colorado River. Hence it is inferred that in one of its early stages the Death Valley lake overflowed southward and southeastward by way of the Ludlow, Amboy, and Danby basins, and into the Colorado River north of Blythe, or perhaps had some less direct connection with the Colorado River.

Mojave River Basin. Water flowing off the northern slopes of the San Gabriel and San Bernardino Ranges, as well as the Tehachapi and lesser ranges farther west, was collected in a number of shallow basins in the Mojave Desert. Most of these lakes probably did not overflow. They are now represented by playas such as the Coyote, Harper, and Rogers dry lakes. However, the Mojave River integrated a number of lakes along its course during the last two glacial episodes, and continued northward into Death Valley. Some 24 miles east of Barstow the river entered an extensive lake whose eastern

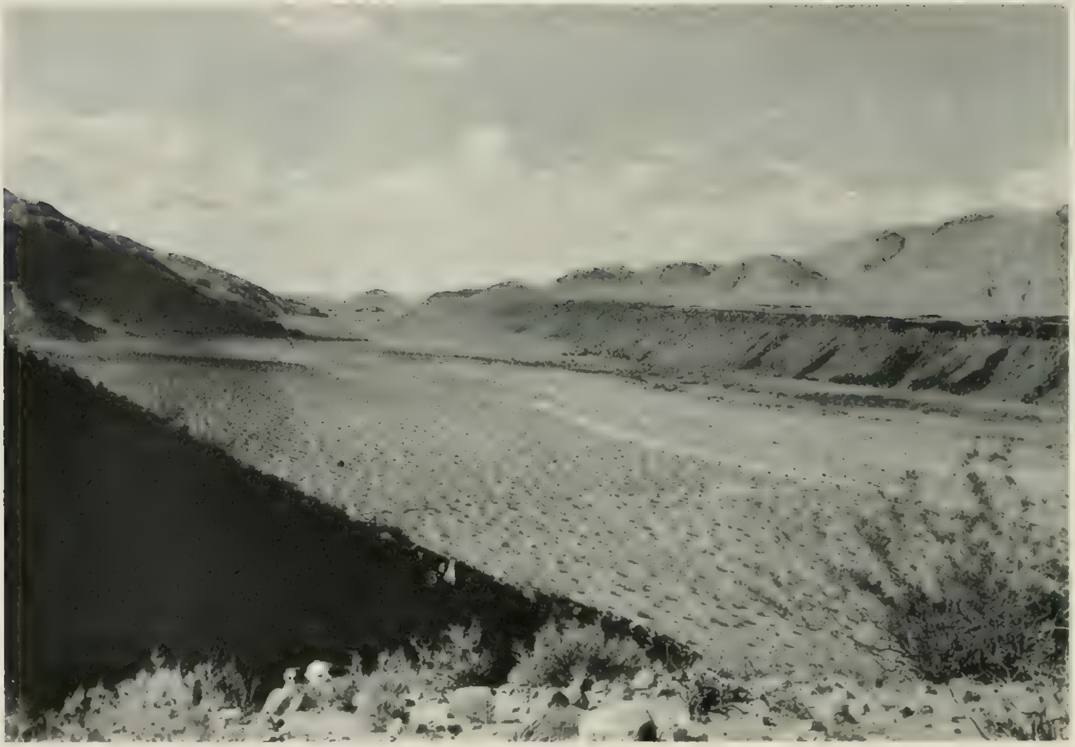

FIGURE 2. Trench cut by the late Pleistocene outlet of Owens Lake, south of Little Lake. Remnant of the basaltic lava flow forms the terrace on the right. Alluvial fans on the left.

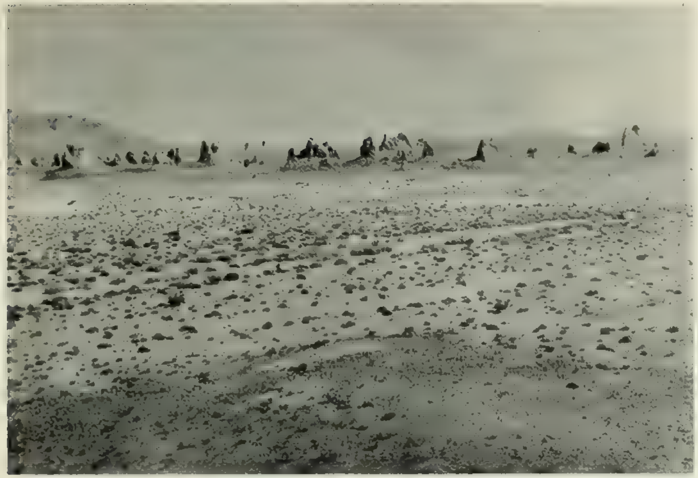

FIGURE 3. Towers of calcareous tufa (the Pinnacles) on a late Pleistocene gravel bar, southwest of Searles Lake.

margin has not yet been recognized. The deep trenching of the lake deposits has revealed many beds of greenish and white clays, which were studied in detail by Ellsworth (1936). Buwalda (1914) has also described vertebrate fossils of Pleistocene age found in these deposits, which he called the Manix beds. On the east side of the basin a well defined gravel bar marks the former shore line, and indicates a lake more than 400 feet deep. There is stratigraphic evidence of two and probably three distinct stages of lake formation, probably corresponding to the Tioga and Tahoe episodes of cold climate.

From the Manix basin the Mojave River descended into a large lake which covered the present Soda and Silver Lake basins. Well-preserved shore terraces and gravel bars on the west and north sides of the playa indicate that the lake was about 28 feet deep during the last cold age. The outlet stream was able to cut only a small gorge as it flowed northward from Silver Lake into Death Valley, and hence it seems probable that the lake overflowed for only a short time, perhaps a few centuries, during the last cold interval.

It has been suggested that, at some time during the Pleistocene epoch, the Mojave River flowed south of east past Newberry Springs and Ludlow, eventually joining the Colorado River. If so, it may have been diverted east and northward by the building of the Pisgah volcano. This theory would account for the fishes in the Death Valley drainage system, without postulating a direct outlet by overflow into the Colorado River.

The copius detritus washed down by the Mojave River through Baxter Canyon has supplied the material that the westerly winds have built into the large sand dunes southeast of Soda Lake. That the Mojave River extends as far as Silver Lake at rare intervals, even under modern climatic conditions, is shown by the fact that an exceptional storm in 1916 formed a lake about 10 feet deep over the existing playa.

Amargosa River. During the glacial episodes cool, temperate conditions must have prevailed in southwestern Nevada. Forests doubtless covered not only the mountains but the high plains as well, and perennial streams descended from the snow-capped high ranges. One of the integrated river systems thereby produced was the Amargosa, a tributary to Death Valley from areas to the east.

On the southeastern side of the Amargosa basin streams from the high Spring Mountain Range formed Mesquite Lake, which discharged northwestward into the Pahrump basin. At one stage (probably the Sherwin or the Tahoe) this lake overflowed into Amargosa Valley at Ash Meadows. Other tributaries from the north also supplied water to the Amargosa River during the cold epochs.

Lake deposits in the Amargosa and Pahrump basins consist of clays and some saline beds, now deeply eroded, and constitute a record of extensive lakes during Pleistocene time. However, as no shoreline features have been recognized, and erosion has destroyed

FIGURE 4. Late Pleistocene gravel spit, on the east side of Death Valley (road to Daylight Pass).

the integrity of the basins themselves, it seems probable that those lakes were of Sherwin age. The Amargosa may have been a permanent stream during the late Pleistocene cold episodes; even now occasional floods reach the Death Valley sink. On the whole, it seems probable that the Amargosa was the least important of the three major branches of the Death Valley river system.

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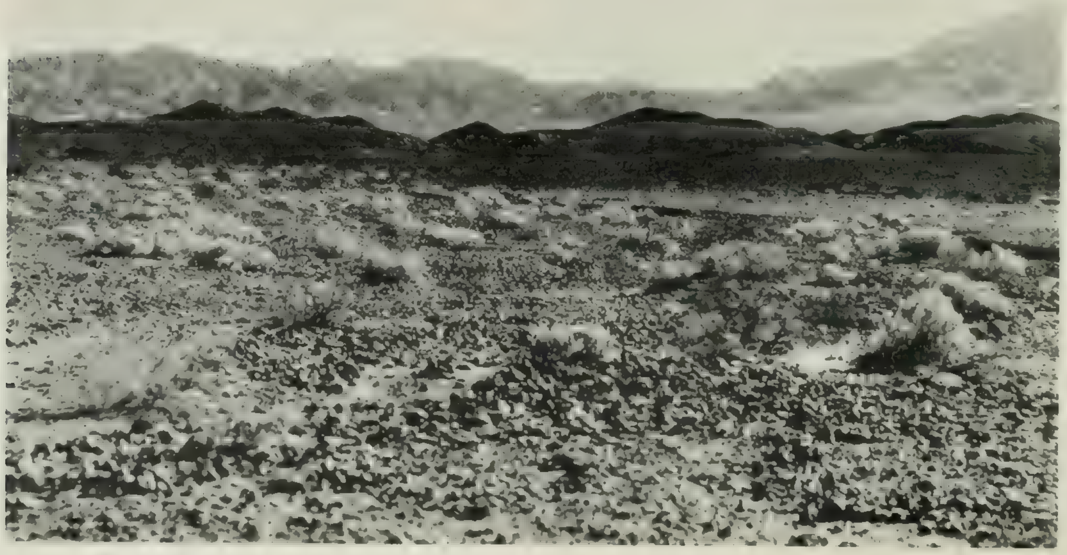

FIGURE 5. Old shore terraces of Lake Manly, north of Furnace Creek, on the east side of Death Valley.

6. PLEISTOCENE GLACIATION IN THE UPPER SAN JOAQUIN BASIN, SIERRA NEVADA

By Joseph H. Birman *

Introduction. The area here considered is high on the western slope of the Sierra Nevada, about 60 miles northeast of Fresno. It is drained by the South Fork of the San Joaquin River and by one of its principal tributaries, Mono Creek, and is about 10 miles north of Florence Lake. The Middle Fork joins the South Fork of the San Joaquin River at a point about 10 miles northwest of the area, whence the general drainage is southwestward to the plains of the San Joaquin Valley (fig. 1). Immediately east of the area is the crest of the High Sierra.

The topography is rugged and altitudes range from about 3,500 feet, at the mouth of the Middle Fork, to more than 13,000 feet on the Sierra crest. The bedrock consists chiefly of granitic rocks of the Sierra Nevada batholith, overlain by widely separated erosional remnants of Tertiary lava flows. The history of these volcanic rocks appears to be complex, and in general they antedate all glacial deposits thus far recognized in the area. Post-Pleistocene volcanism is attested by abundant pumice fragments widely distributed over the present surface.

Valleys tributary to the South Fork of the San Joaquin River are typically narrow, steep-walled gorges, although Mono Creek, of principal interest in this report, has a widely flaring mouth. The South Fork itself occupies a narrow gorge incised in a fairly wide, rounded valley several thousand feet deep. This inner gorge is about 200 feet deep near Florence Lake, and about 3,000 feet deep at the mouth of the Middle Fork. Its walls are very steep, in many places virtually inaccessible. The gorge is one of the most spectacular erosional features of the area.

Cutting of the inner gorge appears to postdate all of the lava flows that have been mapped in the area. On the other hand, it definitely antedates all but the earliest of the glacial episodes thus far recognized. Its age relative to the oldest of the glacial deposits has not yet been satisfactorily determined.

The geologic map (pl. 1) shows the distribution of bedrock and glacial deposits in the areas of Vermilion Valley and lower Mono Creek. Although the map area is but a small part of the broader area considered in this report, it is one of particularly well exposed Pleistocene deposits that seem to be typical for this part of the Sierra Nevada. The map is based upon field studies made chiefly during the summers of 1950 and 1951; this work was done under the auspices of the Southern California Edison Company, and the map is reproduced with the permission of this organization.

The glacial deposits can be divided into three groups based on character and distribution of their constituent materials. Deposits of Group I, the earliest recognized, consist of scattered erratic boulders on slopes and ridge crests high above the major streams. Distribution of these erratics seems to reflect little if any control of the glaciers by the drainage system now established.

Deposits of Group II include extensive, well-developed moraines and associated accumulations of outwash distributed along existing stream valleys. These deposits appear to represent three distinct ice advances separated by episodes of partial or complete withdrawal.

Group III contains the youngest glacial deposits in the region. These have not been recognized in the map area, and appear to be confined mainly to cirques at or near the main crest of the Sierra Nevada. They consist of moraines that are very fresh in appearance, and seem to represent two distinct but very minor ice advances. They probably are of post-Wisconsin age.

Deposits of Group I. Glacial deposits of Group I are found wholly outside the areas of younger ice advances. Except for a few local patches of material tentatively identified as till, the deposits consist entirely of erratic boulders and blocks. Through consideration of such factors as topographic relationships and respective compositions of boulders and bedrock, the erratics can be distinguished from boulders that have been weathered out of bedrock in place, or that have been transported downslope by non-glacial processes.

Erratics of Group I in the Vermilion Valley area are found north of Twin Meadows at altitudes of about 8,500 feet. The granitic bedrock upon which these boulders rest is extensively weathered, and granular disintegration has progressed to points several inches beneath the surface. Many weathering pits and pans are present, and some of them are as much as 6 inches deep. Basic inclusions protrude 5 or 6 inches above the surrounding rock surfaces, and some of these inclusions, having weathered out entirely, lie loose upon the surface. Rock pedestals also are present. No glacial polish is preserved. Weathering of this general magnitude has not been found within the areas of the younger glaciations.

Deposits of Group II. Geomorphological criteria indicate that the moraines of Group II represent three major ice advances separated by episodes of partial or complete withdrawal of ice. Lateral moraines of the earliest advance are the largest and most conspicuous in the area. Some are ridges 200 feet to 300 feet high, as, for example, the outermost moraines surrounding the Devil's Bathtub (pl. 1), but most are 50 feet to 100 feet high. Moraine ridges of this advance form the crest of the divide between Vermilion Valley and lower Graveyard Meadow. These moraines can be traced westward through Twin Meadows, where they form six distinct ridges. West of Warm Creek Meadow the moraines coalesce to form a wide compound ridge easily seen from points across the valley on the Florence Lake road.

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During this early advance, Bear Creek glacier merged with Mono Creek glacier before joining the San Joaquin trunk glacier, by overwhelming nearly all of Bear Ridge south of Vermilion Valley. The San Joaquin trunk glacier, joined by Mono Creek and Bear Creek ice, flowed northwestward to a terminus within the inner gorge of the river at a point about 2 miles downstream from the mouth of the Middle Fork.

Exposures of bedrock glaciated during this advance are not extensively weathered. Weathering has progressed sufficiently, however, to destroy almost all glacial polish. Basic inclusions protrude only 2 or 3 inches from the surfaces of the granitic rocks. The moraines are moderately dissected by gullies 10 feet to 70 feet deep, depending on size of streamlet and topographic setting. In general, these moraines are distinctly more dissected than any of the younger moraines. The once continuous loops of the recessional moraines have been breached or destroyed entirely.

Deposits of the next ice advance within this group are well preserved on Manzanita Ridge in the Vermilion Valley area. The moraines are somewhat smaller than those of the preceding advance, and are 25 feet to 50 feet high. They are less dissected, and are somewhat more bouldery. Weathered boulders are distinctly less abundant than those on the moraines of the preceding advance, and glacial polish is locally preserved.

Glaciation during this advance was less vigorous than that of the preceding advance. The Bear Creek glacier did not completely override Bear Ridge, although several transept glaciers spilled northward through saddles to join the Mono Creek glacier. The Mono Creek glacier, also less vigorous, was deflected northward by a lobe of the San Joaquin glacier that occupied the wide mouth of lower Vermilion Valley. The terminus of the Mono Creek glacier was at Warm Creek Meadow (pl. 1). The terminus of the San Joaquin trunk glacier lay within the inner gorge of the river a few miles upstream from the mouth of the Middle Fork.

The last ice advance of this group is represented in lower Vermilion Valley by excellent arc-shaped moraines, most of which are 5 feet to 10 feet high. Moraines of this glaciation also are found in the saddles on Bear Ridge, in Graveyard Meadow, and at the Devil's Bathtub, where a low, undissected end moraine forms a natural dam for the lake (pl. 1).

The moraines are distinctly more bouldery in appearance than are those of the preceding advances. Relatively few weathered boulders are present, and glacial polish is abundant on the bedrock. Dissection of the moraines is negligible except where they are crossed by Mono Creek and other main axial streams, and the arcs are nearly complete across the valleys.

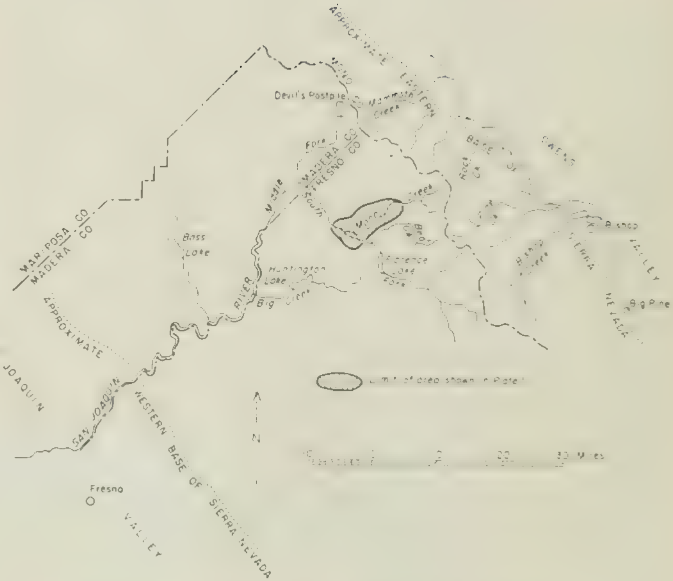

Figure 1. Index map of part of the Sierra Nevada showing area included in plate 1.

Glaciation was much less extensive than in the preceding ice advances. Although Bear Creek glacier joined the San Joaquin trunk glacier, the Mono Creek glacier failed by a narrow margin to reach an eastward-extending San Joaquin lobe, which occupied the mouth of lower Vermilion Valley (pl. 1). The San Joaquin trunk glacier terminated near the mouth of Mono Creek.

Deposits of Group III. The earlier of the two sets of deposits assigned to Group III occur within a mile or so of cirques high on the Sierra crest. Glacial polish is strikingly abundant and excellently preserved. Slopes of the moraines are stabilized, and a thin mat of vegetation is present. A little soil has developed on the moraines, even though they consist mainly of boulders.

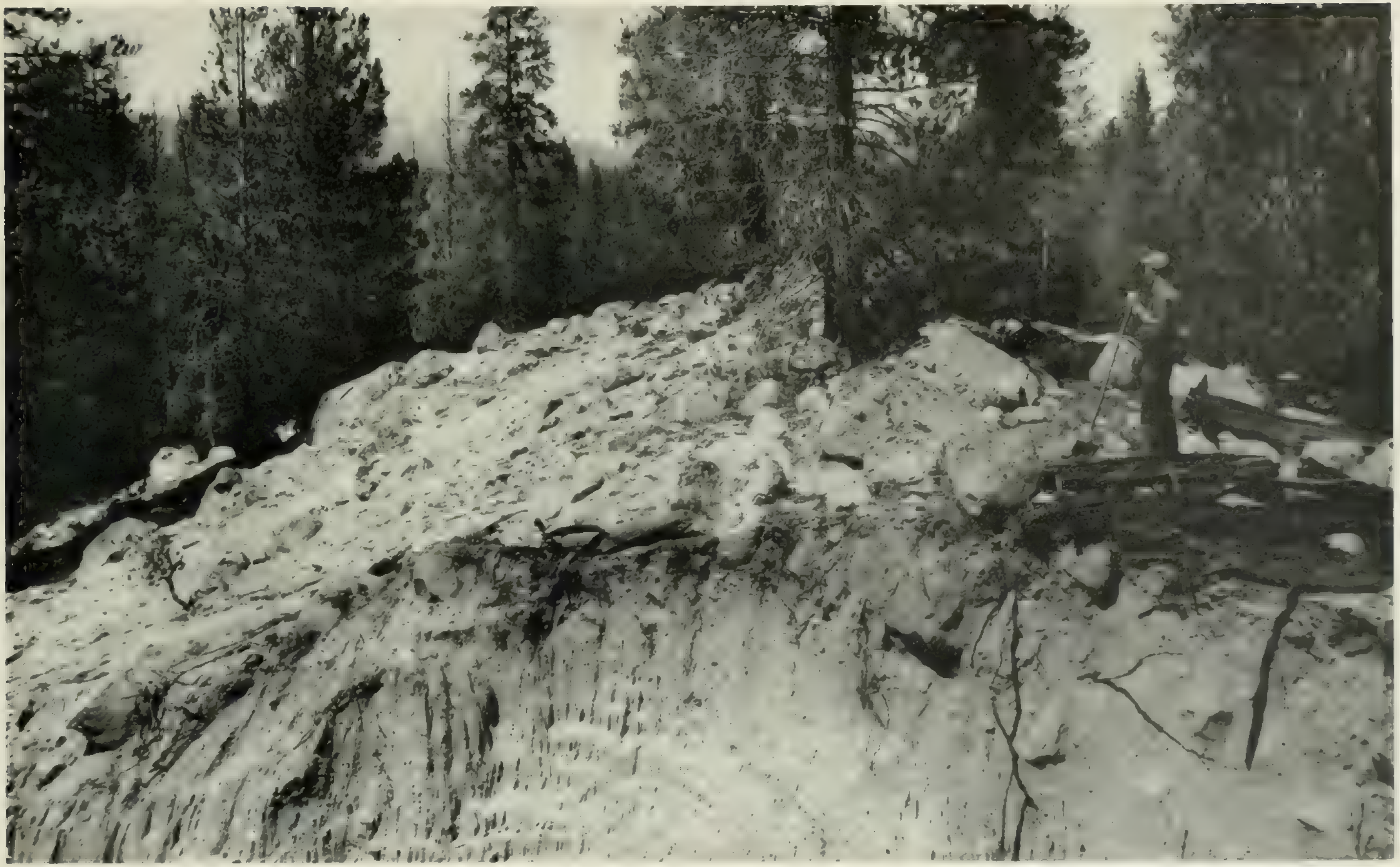

FIGURE 2. Upper part of bulldozer cut, showing cross section of one of the Group II late end moraines on the floor of Vermilion Valley. This moraine rises 20 feet above the floor of the valley; its core consists of stratified outwash, and is overlain by a veneer of till. Distribution and deformation of materials suggest ice push was prominent in the formation of the moraine; direction of ice motion was right to left. View is north along crest of moraine. *Photo by T. M. Leps, Southern California Edison Company.*

Deposits of the later set are confined to the cirques themselves. Most surround the toes of small cliff glacierettes, from which they are separated by a well-defined fos. Although they have the general appearance of rock glaciers, the writer believes that their formation, at least in some instances, was in response to earlier action of the cliff glacierettes which they surround. Slopes are unstable, there is no soil, and ice is present in the interstices of the boulder masses. The deposits give much evidence of a very recent origin.

Tentative Correlations. This report describes an investigation not yet concluded, and the correlations here suggested must be regarded as highly tentative. The relative age assignments are based mainly on differences in degree of weathering of granitic boulders in the deposits, on the degree to which the original form of moraines and other depositional features has been preserved, on the respective positions of various depositional features, and on differences in the nature of glaciated surfaces of the bedrock.

The erratics of Group I may be equivalent in age to the pre-Wisconsin stage proposed by Matthes (1930), or to the McGee stage proposed by Blackwelder (1931). Of Group II, the earliest advance may represent either the Sherwin or the Tahoe stage (Blackwelder, 1931). The latest moraines of Group II may be of Tioga age (Blackwelder, 1931). The moraines of Group III are most likely of post-Wisconsin age.

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7. MARINE TERRACES OF THE VENTURA REGION AND THE SANTA MONICA MOUNTAINS, CALIFORNIA

By William C. Putnam *

Introduction. More than half a century ago, Andrew C. Lawson, following a voyage by steamer along the California coast and a short sojourn in southern California, was prompted to write what is still one of the more provocative papers on Coast Range geology (1893). He was greatly impressed by the giant's stairway of 13 wave-cut terraces that are such a prominent element of the seaward side of the San Pedro (Palos Verdes) Hills, as well as by the even more striking set of treads and risers that interrupt the slopes of San Clemente Island. He rightly sensed the important role these terraces play in the story of post-Pliocene diastrophism of coastal California.

Despite the early interest of such pioneers of southern California geology as Lawson, H. W. Fairbanks (1897), and W. S. T. Smith (1900), all of whom described the coastal terraces of southern California and emphasized their unique characteristics and their importance in the evolution of the landscape, it is most surprising that in the decades to follow there were almost no systematic investigations of this aspect of southern California geology. In fact, not even to this day have the terraces been studied in adequate detail for long stretches of the southern California coast or for the off-lying islands. Two recent studies, the first by Woodring and others (1946) and the second by Upson (1951), have involved the terraces of the Palos Verdes Hills and the Santa Barbara coast, respectively, but they are alone in providing detailed descriptions of terrace morphology.

The Palos Verdes terraces are especially interesting because they are veneered with fossiliferous marine gravels to the uppermost, or thirteenth, terrace at an altitude of 1,300 feet. As Woodring points out, fossils preserved in these terrace gravels are almost entirely those of forms that are still living in waters off the southern California coast today. A similar situation exists with respect to fossils in the terrace gravels of the Santa Barbara and Ventura regions, except that they have not been found at such a high altitude as on the Palos Verdes Hills. Upson reports them up to an altitude of 200 feet and the writer (1942) has found them 700 feet above sea level on the flanks of Rincon Mountain in the Ventura region.

The few past studies of terraces in the Ventura region and the Santa Monica Mountains have been, in the main, ancillary to investigations of other features. Nevertheless, a few generalizations can be made about this aspect of California coastal geology. They should be regarded as tentative, and it is hoped that the necessary field work will soon be done to test them more fully.

General Relations. Marine terraces are better known along the Ventura coast than in the Santa Monica Mountains, and for this reason most of the following statements apply to the more westerly area. Even there, however, the available information is most imperfect, owing mainly to the following factors:

(1) The terraces are very narrow—few are as much as 1,000 feet wide.

(2) The unequivocally marine sands and gravels on the terrace surfaces rarely are more than 10 feet thick, and generally are much less.

(3) Almost all of the terrace surfaces and their thin veneers of marine sediments are capped by seaward-sloping blankets of alluvial-fan gravels, which at their landward end may be more than 100 feet thick. For this reason the critical shoreline angle (base of the sea cliff) (Davis, 1933), is almost invariably concealed.

(4) The alluvial deposits commonly make a continuously sloping surface from one terrace down to a level three or four treads lower, thus completely obscuring intervening terraces.

(5) Finally, all the capping of both marine and non-marine detritus has been stripped from some of the higher terraces, leaving only rock-surfaced benches or ridges at coincident altitudes. Whether or not these actually are terrace levels is a question that is difficult indeed to resolve.

In spite of these handicaps, the evidence is unequivocal that marine terraces do exist, and that in the Ventura region they very likely rise to altitudes of about 1,200 feet. Their maximum altitude in the Santa Monica Mountains is not known at present, but there is reason to believe that they rise there to heights of perhaps 800 feet above sea level (Goldberg, 1940).

Available evidence in the Ventura region strongly suggests that the terraces are warped. At the northern end of this area they are almost certainly inclined toward the Santa Barbara coastal plain, and at the southern end they probably are warped downward toward the flood plain of the Santa Clara River. That the coastal terraces may be warped is not surprising in view of the recency of deformation in this area, and in this respect they are similar to the Palos Verdes terraces as described by Woodring. These dip toward the Los Angeles plain at the northern margin of the hills, and in one instance the terrace surface is inclined as much as 27°. No terraces in the Ventura region appear to dip as steeply, but they are sufficiently arched or broken by faults to preclude much hope of correlating at least the higher ones with levels elsewhere.

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The status of marine terraces in the Santa Monica Mountains is even more obscure. W. M. Davis (1933) almost certainly oversimplified the problem when he recognized but two marine platforms, the higher at altitudes of about 200 feet. He believed also that these benches were inclined uniformly westward, ultimately to sink below sea level near the western end of the range. Davis deduced an origin for these wave-cut platforms that was based on eustatic swings of sea level during the glacial and interglacial stages of the Pleistocene epoch. If this interpretation were to hold, these levels must be of more than local significance, and the periods of terrace cutting would extend well back into the Pleistocene.

This clearly does not appear to have been the case in the Ventura region. For example, marine terraces in the City of Ventura truncate near-vertical siltstone, sandstone, and conglomerate beds of early Pleistocene age. This evidence indicates that the time of terrace formation, rather than extending far back into the Pleistocene, is but an episode that occurred very near the close of the epoch. Within the span of this shortest chapter of geologic time, the following major events can be recognized at Ventura: (1) deposition of several thousand feet of marine and non-marine sediments; (2) their deformation, along with all other rocks of the region, by large- and small-scale faults and by tight folds with steep flanks, many

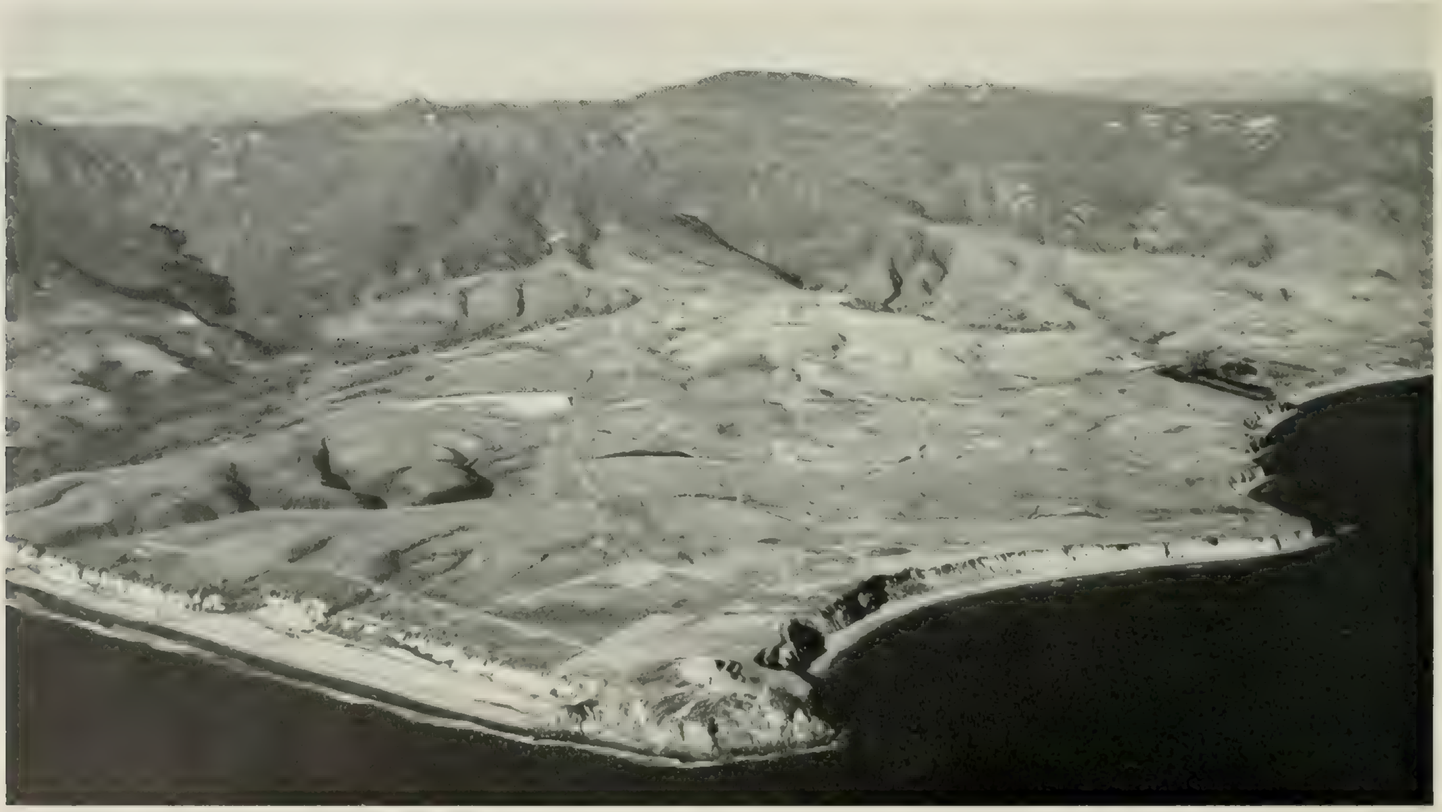

Figure 1. Dissected marine terraces in the Point Dume area. Remnants of higher terraces show on the lower spurs of the Santa Monica Mountains in the background. *Pacific Air Industries photo.*

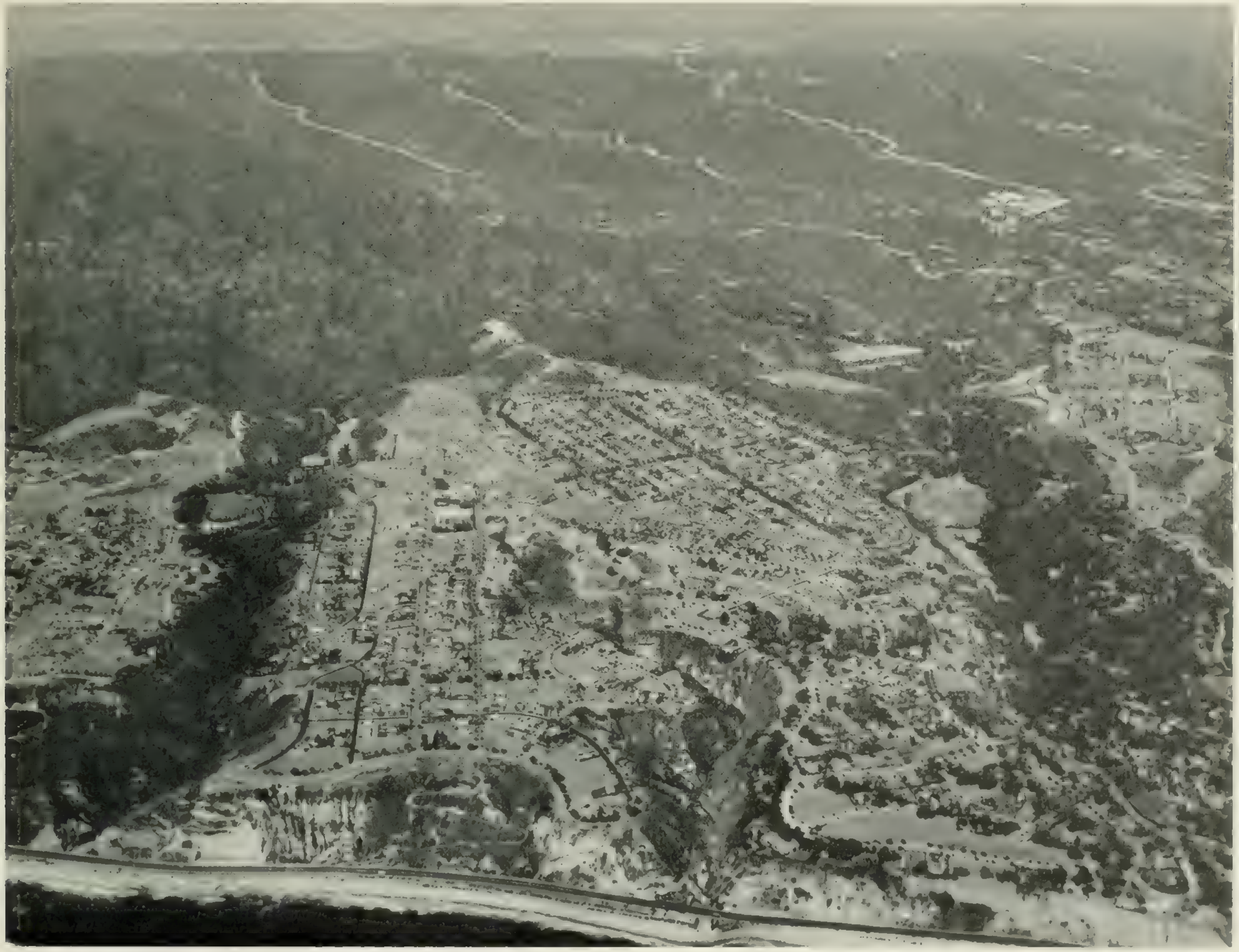

FIGURE 2. Terraces developed on Quaternary and Tertiary sediments, Pacific Palisades. Settled areas emphasize the principal terrace surfaces. Santa Monica Mountains in background. *Pacific Air Industries photo.*

of which are overturned; (3) erosion that reduced the region to one of moderate relief; and (4) a pulsatory regional uplift responsible for the development of coastal marine terraces and their fluviatile counterparts inland. That this uplift, though widespread, was not uniform is indicated by the extent to which the terraces are arched locally.

Dating of the less well-known terraces of the Santa Monica Mountains is more difficult, but their elevation appears to have been essentially synchronous with that of the Palos Verdes Hills and the mountainous part of the Ventura coast. In both of these areas the uplift has been established with certainty as late Pleistocene, in the generally accepted sense of the term as it is used in southern California.

To what extent these terraces are the result of regional uplift and to what extent they are eustatic is an open question, and in areas as mobile as this it will probably remain unresolved for a long time to come. Upson holds the view that levels below the 200-foot contour in the Santa Barbara area may well be correlatives of similar marine platforms described elsewhere in the world. If this interpretation is substantiated and these levels indeed can be related to glacial stages, he is correct in pointing out that events preceding the terrace cutting that were heretofore assigned to the Pleistocene epoch in southern California very probably antedate the beginning of glaciation. This also was pointed out some years ago by Eaton (1928). Whether this is the case or not, the question cannot be answered in the light of present knowledge of the geology of southern California.

Because of the degree to which terraces below the 200-foot level have been warped in the Ventura area, it is not likely that they will lend themselves satisfactorily to attempts at interregional correlation. However, at lower altitudes they may well be eustatic, and it is here that the best case can probably be made for such an origin. One of the better exposed low-altitude terraces in the Ventura region lies a short distance south of Rincon Mountain, where steeply dipping Pliocene strata are bevelled by a broad wave-cut bench at an altitude of 40 feet (Putnam, 1940). Similarly, at the head of Santa Monica Bay waves no longer reach the base of a prominent line of near-vertical cliffs, known locally in the City of Santa Monica as the Palisades, that have been developed in virtually unconsolidated alluvial-fan gravels. Both of these wave-cut features, as well as many other bits of evidence, testify strongly to a very recent withdrawal of the sea to a vertical extent of 30 or 40 feet. Judged in terms of similar occurrences along other continental and insular coasts of the world, these features may well be results of eustatic lowering of sea level.

Conclusions. The seaward-facing slopes of the Santa Monica Mountains and the hilly parts of the Ventura coast are interrupted by a discontinuous flight of narrow, wave-cut platforms that bevel severely deformed sedimentary and volcanic rocks. At Ventura these rocks include strata of early Pleistocene age, so that the period of terrace cutting was during the late Pleistocene.

Exposed on some of the terraces are the initial coverings of fossiliferous marine sands and gravels, but in most places these, as well as the entire platforms, are concealed by blankets of alluvial-fan gravels. These gravels make determination of the absolute number of terraces and their altitudes difficult, if not impossible. In the Ventura area, terraces can be recognized with some confidence to an altitude of 1,200 feet, but their maximum altitude is not now known in the area of the Santa Monica Mountains.

The higher terraces in the two areas are most likely the result of essentially contemporaneous regional uplift, but individual levels are almost certainly not synchronous. Further it seems unlikely that they ever will be correlated for any great distance with terrace levels elsewhere, because it is established rather certainly in the Ventura region that they have been warped.

Two large problems awaiting solution in coastal southern California are: (1) establishing the time of terrace cutting in terms of the glacial standard of Pleistocene chronology; and (2) determining to what degree the terraces are the result of diastrophism, as opposed to eustatic swings of sea level. Data now available do not offer much hope for satisfactory treatment of these problems.

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8. THE NATURE OF CIMA DOME*

By Robert P. Sharp†

INTRODUCTION

In the Mojave Desert of southeasternmost California is a remarkably smooth, symmetrical rock-alluvial dome which takes its name from Cima on the Union Pacific Railroad. Lawson (1915, pp. 26, 33) cited Cima Dome as a prime example of a panfan, but Thompson (1929, p. 550) later showed that its upper part is bare rock. Davis (1933, pp. 240-243) considered it a fine example of a convex desert dome evolved from back-wearing of a fault block, but this concept is contradicted by the geological relations (Hewett, 1954), which throw more light on the nature and origin of Cima Dome than do geomorphological theories.

Field studies reported briefly herein suggest that Cima Dome is essentially an upwarped, stripped, and slightly eroded part of an extensive prevolcanic erosion surface, probably of late Pliocene age (Hewett, 1954). It is not convex, except in slight degree at the very summit, and owes its existence largely to the nature of the underlying bedrock. These are tentative conclusions as the work is still in progress.

The list of persons contributing to this study includes D. F. Hewett, C. H. Dix, G. W. Potapenko, William Otto, C. R. Allen, R. L. Nelson, J. R. Reese, C. W. Faessler, Pierre St. Amand, G. I. Smith, A. R. Sanford, G. P. Eaton, M. F. Meier, Carel Otte, and Jean T. Sharp. Appreciation is expressed for their aid, counsel, and assistance.

Location and Physical Setting. Cima Dome lies near the California-Nevada border and is clearly visible 12 miles southeast of U. S. Highway 91 between Baker and Las Vegas and six miles northwest of the Union Pacific Railroad at Cima. The form of the dome is expressed in generalized fashion in T. 14 N., R. 13 E. of the Ivanpah quadrangle map (1:250,000). It lies on the axis of an upland that comprises the Ivanpah and Kelso Mountains. Slopes of the dome drain east to Ivanpah Valley, south to Kelso Valley, and north to Kingston Wash and the Amargosa River.

Topographic Relations. A conservative measure of the area of Cima Dome is 75 square miles. Its summit is 5,795 feet above sea level, and the generally ill-defined base of the dome lies at altitudes of approximately 5,000, 4,400, 4,500, and 4,000 feet respectively on the northeast, north, west, and south. Cima Dome thus rises 800 to 1,800 feet above its base. Angles of slope measured by transit range from as little as 0° 57′ near the base to 4° 40′ near the summit. The slopes are remarkably smooth except for a local relief of 5 to 25 feet toward the top, and symmetry of the dome is impressive (fig. 1). A few bedrock residuals rise on the flanks, of which Teutonia Peak on the northeast is the largest, being 300 to 400 feet high. Other knobs rise 50 to 200 feet above the south and southwest slopes.

The profile form of Cima Dome is a critical point. Viewed from a distance it looks distinctly convex, and Davis (1938, pp. 1389, 1413) states that the uppermost 700 feet, about half the height, is convex. Bryan (1940, pp. 261-262) questioned the inferred convexity of Cima Dome, and to settle the matter two 10-mile profiles have been surveyed by transit and stadia across Cima Dome (fig. 2). These show clearly that the dome consists of concave or nearly straight slopes intersecting in a slightly blunted crest. Essentially,

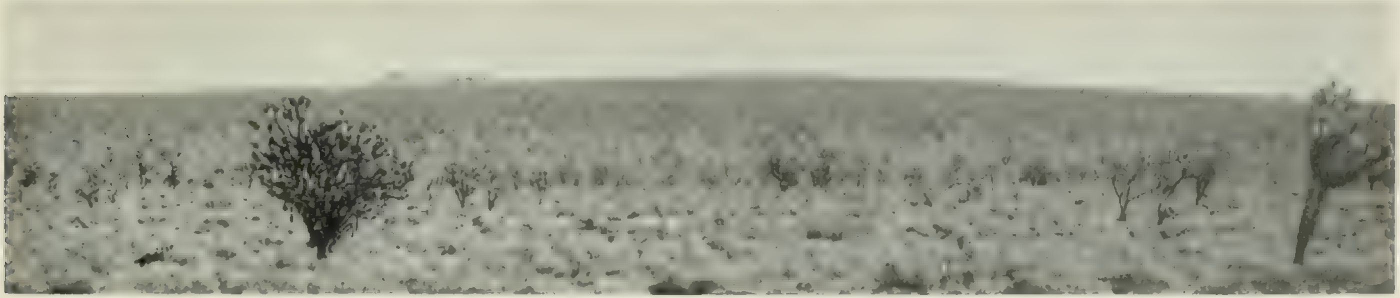

Figure 1. Cima Dome viewed from the southwest, showing residuals of resistant rock on its flanks.

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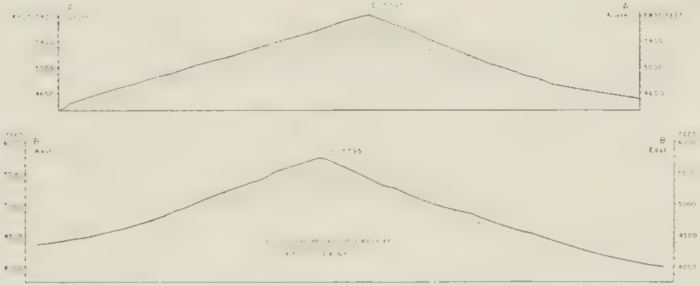

FIGURE 2. Transit-stadia profiles across Cima Dome, location shown on figure 3. Straight reference lines above surface reveal concavity of slopes. (These surveyed profiles are not compatible in detail with the contours in figure 3, which are adapted from an earlier map.)

no convexity is recorded in the north-south profile, and the east-west profile shows local convexity only in the uppermost 25 feet. The complicated argument development by Davis (1938, pp. 1391-1392) to explain convex domes has no application here.

BEDROCK-ALLUVIUM RELATIONS

The bedrock-alluvium contact has been mapped in some detail on air photos, and these data are represented in grossly generalized form on figure 3. This contact lies at altitudes 600 to 700 feet below the crest, roughly half way down the slope, and approximately 30 percent of the dome is bare rock.

The thickness of the alluvium and the form of the buried bedrock surface are of interest, particularly on the south and southeast flanks of the dome, for the bearing they may have on the possible fault-block nature of the Cima Dome mass (Davis, 1933, p. 240), and on the existence of a suballuvial bench (Lawson, 1915, p. 34). In an attempt to learn something of these matters, an electrical resistivity survey was made along the southeast part of the profile BB′ (fig. 2), Subsequently this same ground and the area farther east-southeast were surveyed by seismic refractions and reflections. Interpretation of the geophysical data is not completed, but preliminary results indicate that the only faults discovered or inferred have the upthrow on the wrong side to support Davis' fault-block argument. The buried rock floor appears to be somewhat irregular and shows no form suggestive of a convex suballuvial bench. The greatest depth of alluvium recorded is 500 to 600 feet, and near the southeastern end of the profile it is underlain by a wedge of sedimentary or possibly volcanic material resting upon the crystalline rocks, which lie about 1,350 feet beneath the surface at the point of greatest depth.

BEDROCK GEOLOGY

Pre-Tertiary Crystalline Rocks. The principal rock exposed on Cima Dome is a coarse, locally porphyritic quartz monzonite which disintegrates rapidly and uniformly under desert conditions. With one or two minor exceptions, all projecting knobs, hillocks, and ridges on the flanks of the dome are composed of other rocks. These include a uniform medium-grained granite, a distinctive highly porphyritic gneissic granite, a gneissic complex, aplite, pegmatite, and trap dikes, quartz veins, and silicified zones in the monzonite. These rocks are all more resistant to weathering and erosion than the quartz monzonite. It is clear there would be no Cima Dome were it not for the existence of this large homogeneous body of monzonite with its property of rapid and uniform disintegration.

Tertiary (?) Rhyolitic Tuff. Along an abandoned road leading west from Cima toward Marl Spring are two small exposures of rhyolitic tuff unlike any other rocks seen in this area. The tuff rests uncomformably on a complex of crystalline rocks resembling the so-called pre-Cambrian material near and south of Cima (Hewett, 1954). These exposures of rhyolitic tuff are probably related to the fault extending west-southwest through Cima (fig. 3).

Cenozoic Volcanics. West of Cima Dome is an extensive volcanic field of at least 26 cones with associated lava flows (Hewett, 1954). Two stages of vulcanism, probably both of Quaternary age, are represented. Most of the cones and some of the flows are very young, possibly late Pleistocene to Recent, and they are built in places on a platform of older flows and pyroclastics, possibly early Pleistocene.

In the eastern part of this volcanic field the older sequence consists of olivine basalt flows and layers of pyroclastics totaling 100 feet in thickness and resting upon a smooth granitic rock floor. This contact has been studied in a dozen different places. In general, the granite shows signs of extensive weathering in the form of a mantle of highly disintegrated, calichified, and locally clay-rich grüs underlain by partly disintegrated granite to depths of 50 to 60 feet. In places, the granite is overlain by 50-75 feet of grüs, bouldery grüs, fanglomerate, or mixed grüs and pyroclastics. The basal volcanics are pyroclastics in some places and flows in others.

The older volcanic sequence has been dissected as much as 200 feet and has been stripped from a considerable area. The younger volcanics consist of cinder cones and basalt flows extruded in part onto platforms of the older volcanics and in part onto a granitic rock surface lying at a lower level.

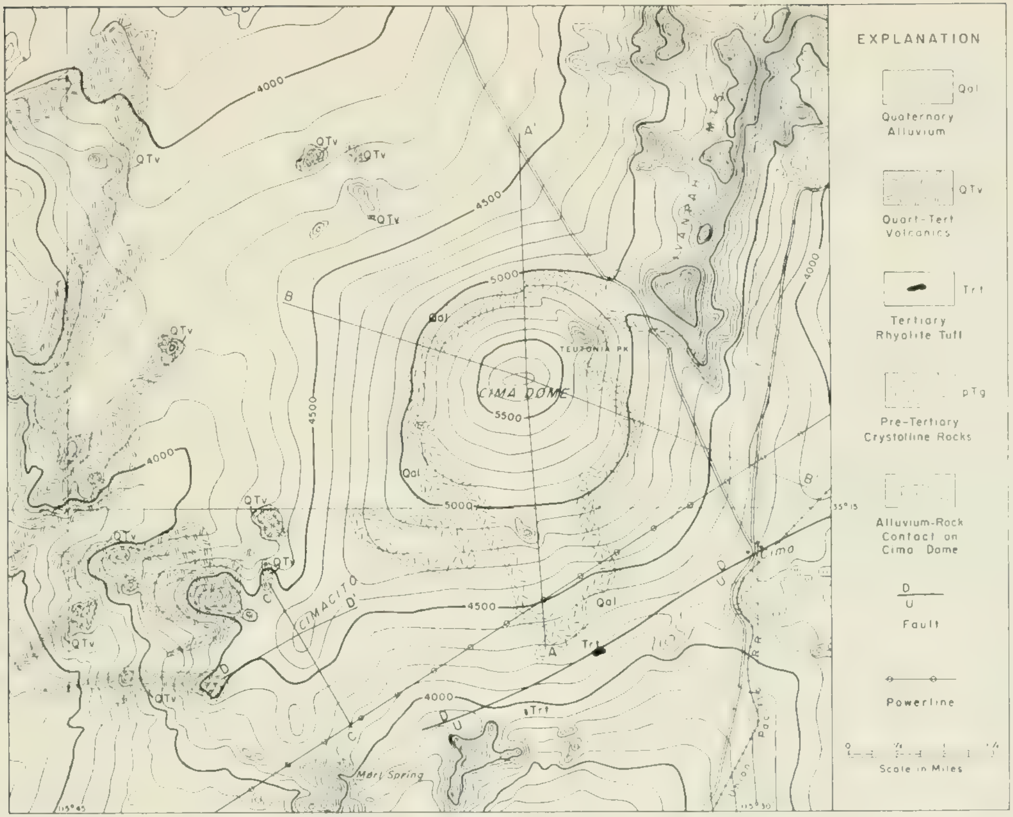

FIGURE 3. Generalized map of pertinent geological relations at Cima Dome.

The significant relations here are: (1) The older volcanics rest on a smooth granitic rock floor mantled with weathered debris which lies 50 to 150 feet above a rock floor graded to the present slopes of Cima Dome. (2) Dips measured in the volcanics suggest deformation by broad, gentle warping, and this impression is confirmed by distant views. (3) The wide distribution of similar volcanics resting on an erosion surface of low relief (Hewett, 1954) suggests that they formerly covered a large area and have been subsequently dismembered by dissection and stripping.

The exposure of volcanics nearest Cima Dome lies at the northwest base, 4.5 miles from its crest (fig. 3). One mile farther northwest is what appears to be a vent of eruption for the older volcanics. More extensive remnants of the volcanics lie west and southwest of Cima Dome at a minimum distance of 6 miles from its summit (fig. 3).

A careful search for volcanic remnants on Cima Dome itself was relatively unproductive. Three small fragments of basalt were found at widely separated places well up on the dome, but one was clearly part of an Indian grinding stone, and they all may be aberrant. A number of trap dikes intrude the quartz monzonite on the west and southwest flanks of the dome, but they are principally hornblende latite or trachyte, and hence probably are not related to the basaltic volcanics.

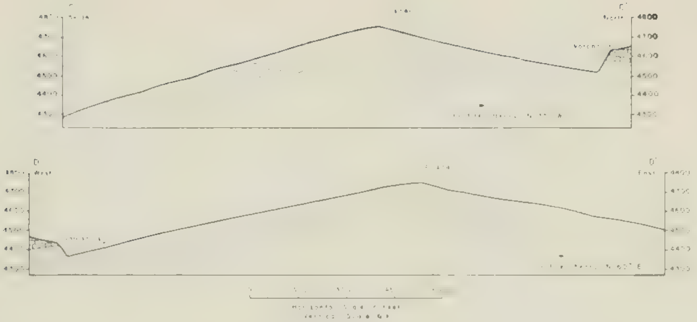

FIGURE 4. Transit-stadia profiles across Cimacito. (These surveyed profiles are not compatible in detail with the contours in figure 3, which are adapted from an earlier map.)

Faults. The only significant fault identified on the surface trends west-southwest through Cima and in essence determines the south base of Cima Dome. Its course is marked by a series of bedrock knobs and ridges and by small outcrops of rhyolitic tuff. A well 700 feet deep in alluvium about 1,600 feet north of rock exposures near Cima confirms the conclusion, drawn from bedrock relations, that the south side of the fault is upthrown. Suggestions of a fault with similar but much smaller displacement lying about one mile farther north have been picked up by the geophysical work. Neither of these faults satisfies Davis' (1933, p. 240) postulate that Cima Dome is the remnant of an uplifted fault block.

THE TESTIMONY OF CIMACITO

Seven miles southwest from the summit of Cima Dome is a much smaller granitic dome herein called the Cimacito for purposes of identification (fig. 3). With minor exceptions, Cimacito is a small-scale counterpart of Cima Dome. It covers only 6 square miles and rises 200 to 400 feet above its base. The slopes of Cimacito are almost straight and intersect without noticeable crestal convexity, as shown on transit-stadia profiles (fig. 4). They are even smoother than the slopes of Cima Dome, local relief hardly exceeding 5 feet anywhere. The cover of detrital grüs is so thin, even on the lower flanks, that the dome can be considered an essentially continuous rock surface. The symmetry is also excellent save for longer slopes to the west and south.

The significant features at Cimacito are remnants of Cenozoic volcanics perched on low hills on its southwestern and northwestern flanks (fig. 4). The volcanic layers dip gently off the dome and rest on a smooth, weathered granitic rock floor 50 to 75 feet above the present surface of Cimacito.

These relations suggest that Cimacito was at least partly covered by volcanics which, following deformation, were dissected and stripped away. The granitic surface was lowered 50 to 100 feet in the process. It seems entirely possible and likely that the volcanics completely covered the dome, but there is no direct proof of this. Noteworthy is the fact that not a single fragment of volcanic rock was found on Cimacito more than 200 feet away from the present volcanic outcrops.

ORIGIN OF CIMA DOME

Data reported above lead to the following interpretations concerning development of Cima Dome. A period of erosion, culminating in the late Pliocene(?), produced an extensive surface of low relief on certain areas of granitic rock in the eastern Mojave Desert. At this time the site of Cima Dome and the region to the west was one of exceptional smoothness owing to the homogeneity and rapid weathering of the coarse quartz monzonite there exposed. Quaternary pyroclastics and lavas were extruded over at least parts of this surface, and subsequent gentle deformation produced broad warps among which was a symmetrical, dome-shaped uplift at the site of Cima Dome. Erosion, initiated by the deformation, stripped the volcanics from large areas and modified slightly the pre-volcanic erosion surface. At Cima Dome perhaps 100 feet of weathered granitic debris and rock were removed, and the slopes of the uplift were converted to smoothly graded concave surfaces. A second period of volcanism did not materially affect the history of Cima Dome.

Briefly, Cima Dome is a remnant of an extensive late Pliocene(?) erosion surface deformed into domical shape and modified slightly by subsequent erosion. The perfection of the dome reflects in large degree the uniformity and nature of the underlying bedrock.

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9. HISTORY OF THE LOWER COLORADO RIVER AND THE IMPERIAL DEPRESSION

By Chester R. Longwell *

TOPOGRAPHIC SETTING

The Colorado River, emerging from the Grand Canyon cut into the Colorado Plateaus, flows west to the Great Bend north of Hoover Dam, and thence generally south to the head of the Gulf of California (fig. 1). From the mouth of the Canyon to the Gulf the distance, as measured along two straight lines intersecting at the Great Bend, is about 370 miles; along the sinuous course of the stream, it is about 450 miles. In this distance the stream grade descends about 900 feet.

Numerous and radical changes in form of the river valley characterize this long stretch through the Basin-Range province. In its course east of the Great Bend the river crosses the Southern Virgin and Black Mountains in deep, narrow canyons; but in the basins on both sides of each range the valley is wide, with side slopes generally low. South of the Great Bend the river traverses a number of open basins, and flows generally parallel to several ranges but transects others in steep-walled canyons, of which the most prominent are Black Canyon (site of Hoover Dam), Needles Canyon (crossing the Mohave-Chemehuevis mountain group), and Aubrey Canyon (crossing the Whipple Mountains). Only a short distance upstream from Yuma the stream crosses the Chocolate and Trigo Mountains in a valley that is narrow but of only moderate depth. Below the vicinity of Yuma lies the vast surface of the delta, marked by many distributory channels, some active and others abandoned (fig. 2).

Northwest of the delta, and in an important way genetically related to it, is an elongate lowland containing the rich agricultural district known as Imperial Valley. Of this lowland a belt 85 miles long and as much as 30 miles wide is below sea level; the Salton Sea, about 20 miles long, occupies the lowest part of the belt, in which the minimum altitude is reported as —273 feet. Encircling the depressed area at elevations 40 to 50 feet above sea level is the well-defined shoreline of a former lake, known as Lake Cahuilla, first reported by Blake (1856); the rich soil of Imperial Valley consists of fine deposits on the floor of the old lake. This entire lowland is merely the lowest part of a complex fault trough which structurally is the northwesterly continuation of the Gulf of California. The San Andreas, San Jacinto, and other major faults extend into the area from the northwest.

Probably the subaerial part of the delta, which acts as a barrier excluding the Gulf water from the depressed area to the north, has varied in height during its growth on a subsiding basement. At present the lowest part of the summit, near a ridge on the west known as Cocopa Mountain, is about 30 feet above sea level. Presumably the barrier was higher while the surface of Lake Cahuilla stood at 40 to 50 feet altitude, since evidence that the lake was fresh is convincing. Perhaps erosion by overflow from the lake reduced the height of the barrier.

According to views published prior to 1930, the delta as it grew isolated the northern part of the Gulf, and under the desert climate the sea water thus ponded soon disappeared through evaporation. Buwalda and Stanton (1930) presented evidence strongly indicating that the Imperial depression sank below sea level after the delta was large enough to keep the sea water from entering. Possibly the depression has been filled more than once with water from the Colorado River, and it is estimated that Lake Cahuilla, the latest body of fresh water to fill the basin, existed only a few hundred years ago.

SIGNIFICANT SEDIMENTARY DEPOSITS

Bedrock in the ranges along the river south of the Great Bend is highly varied. Abundant metamorphic rock, much of it pre-Cambrian, is cut by numerous intrusive igneous bodies, and volcanic rocks of many types are widespread. Pre-Cenozoic sedimentary rocks are not found in most of this area, although there are isolated remnants of Paleozoic limestone and argillite in the Riverside and Whipple Mountains.

The most cogent information bearing on the history of the river comes from sedimentary deposits of late Cenozoic date, some distinct units exposed along the river and several of its tributaries, other units in parts of the area around the Salton Sea.

Muddy Creek Formation. Exposed widely along the river between the Black and Grand Canyons, and extending far to the north along the Virgin and other tributary valleys, is a thick succession of clastic deposits interbedded with gypsum, anhydrite, halite, and glauberite (Longwell, 1928, 1936, 1946). The most conspicuous part of this Muddy Creek formation consists of buff-colored, weakly indurated siltstone and sandstone, deposited partly in lakes and probably partly on playa flats. These typical arid-basin sediments, spread widely athwart the river's course, indicate that the Colorado was not in its present location as a through-flowing stream while the sediments were accumulating. Bedded gypsum and anhydrite in the lower part of the formation are hundreds of feet in total thickness, suggesting a considerable time required for deposition. Vertebrate fossils from siltstone above most of the salt and gypsum are tentatively assigned to the Miocene (Stock, 1921).

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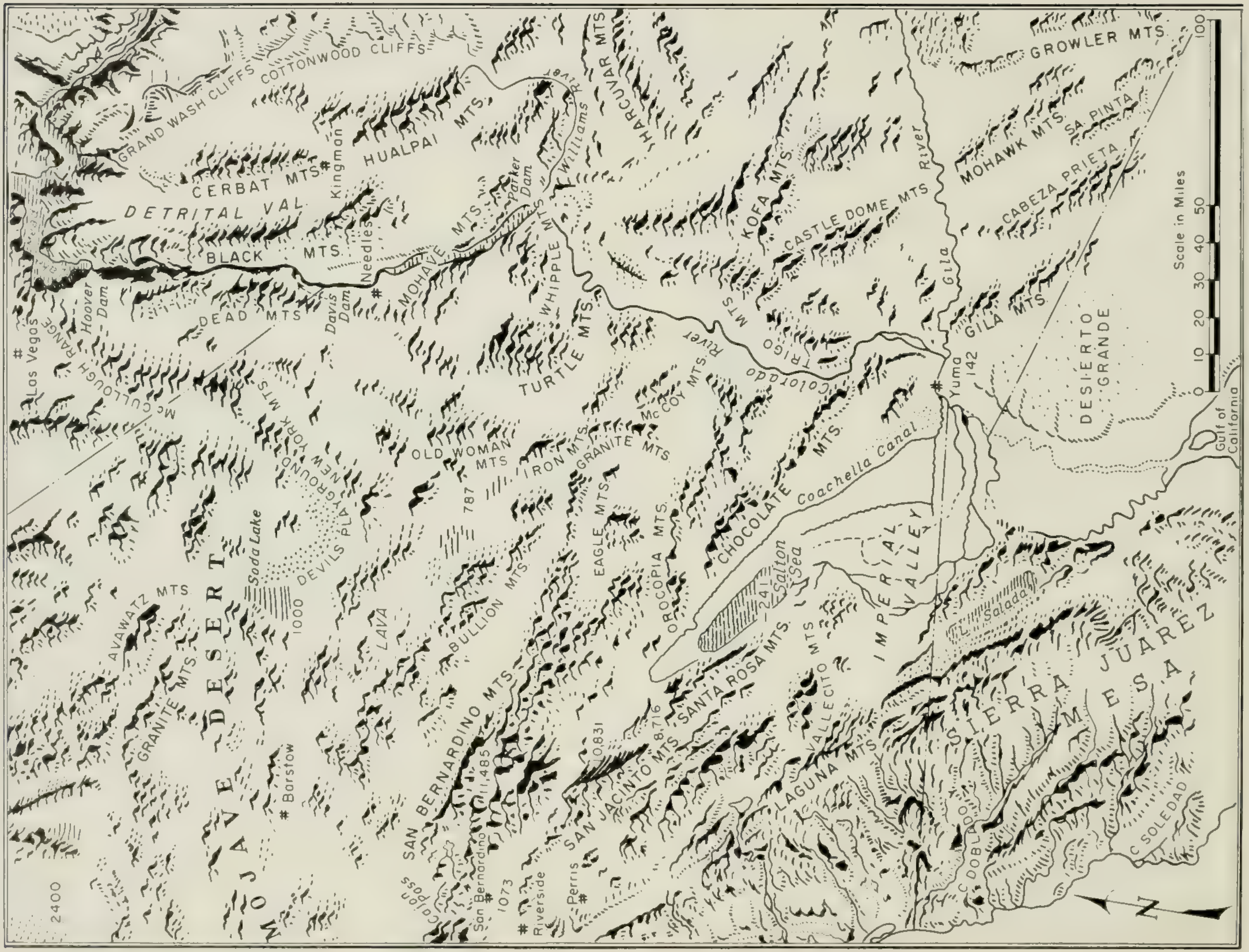

FIGURE 1. Regional setting of the lower Colorado River (slightly modified from Landforms Map of the United States by Erwin Raisz, by permission of Ginn & Co.).

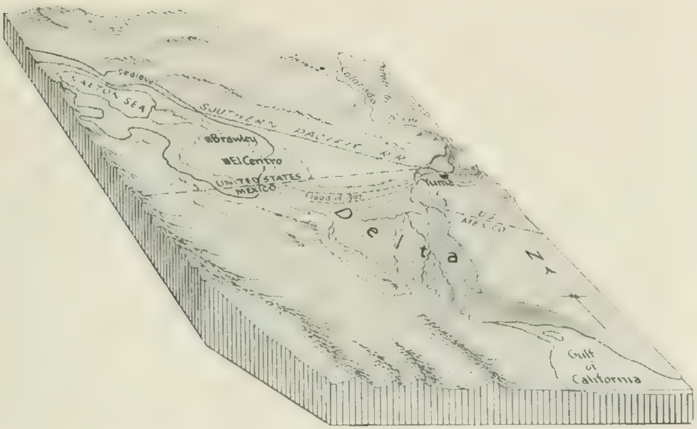

FIGURE 2. Block 200 miles long showing delta of Colorado River and surrounding features, including boundary of area below sea level north of delta (R. F. Flint).

Imperial Formation. A marine deposit with maximum thickness of about 2,000 feet forms large outcrops in the hills around the Salton Sea. Woodring (1931) pointed out that the buff-colored silt and sand making up the major part of this Imperial formation made its appearance in the basin abruptly, and probably was brought in by the ancient Colorado River. Similarity of the Imperial silts to the buff-colored beds in the Muddy Creek formation suggests that the Colorado acquired its present through-flowing status shortly after deposition of the Muddy Creek beds, and that its earliest deposits in the Gulf region are represented in the Imperial formation. As that formation has been variously assigned to parts of the Miocene (Woodring, 1931; Tarbet, 1951) and of the Pliocene (Vaughan, 1917; Kew, 1920; Durham, 1950), the hypothesis of its genetic relationship to the Muddy Creek is plausible. Wilson (1948) presents evidence suggesting that the Gulf of California was absent or of limited extent until late Miocene time; he also regards the Imperial formation as probably Pliocene in age.

Stream Deposits. The oldest deposits definitely assignable to the Colorado River are gravel, sand, and silt that are partly indurated, unconformable on Muddy Creek beds, and locally much deformed (Longwell, 1936, 1946). Camel bones from these deposits are either Pliocene or Pleistocene. On this basis the present course of the river seems to be no older than Pliocene. Possibly, as suggested by Hunt (1946), exceptional aridity in Miocene time ended an earlier through-flowing stage, direct evidence of which may be concealed by the later basin fill.

Chemehuevis Lake Beds. One of the most significant deposits exposed along the river, from the mouth of the Grand Canyon downstream at least as far as the basin south of the Whipple Mountains, consists of a lower member made chiefly of laminated clay and silt, and an upper member in which fine, cross-bedded sand is predominant. Remnants of this weak material, capped by sheets of river gravel, extend from near river grade to altitudes slightly above 1,500 feet. Probably the conspicuous gravel of these terraces led W. T. Lee to call the entire deposit the Chemehuevis gravel (1908). Clay in the lower member is strikingly like that now accumulating on the floor of Lake Mead, and the sand above is like that in the delta now building at the head of this lake. Clearly the Chemehuevis deposit represents a vanished lake that formed after the river valley was developed to essentially its present form. As the obstruction causing the lake was removed the river cut down by stages recorded in wide terraces. The return to its earlier grade was marked by many local shifts in location of the channel, as in the vicinity of Davis Dam where Chemehuevis clay and silt fill a conspicuous part of the old river trench.

The largest Chemehuevis remnants are in protected embayments of rugged hill country like that around Davis Dam (fig. 3). An excellent exhibit of what appears to be the highest gravel terrace

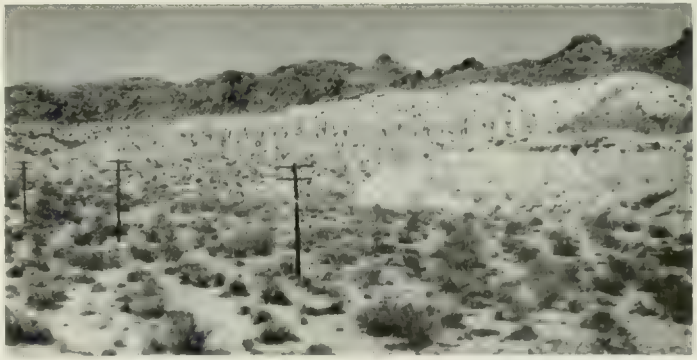

FIGURE 3. Typical remnant of Chemehuevis deposit laid against old rocks of Newberry (Dead) Mountains, 2½ miles northwest of Davis Dam, about 400 feet above Colorado River. Lower part of outcrop laminated clay; sand at upper right.

connected with the lake history lies on the east flank of Sugarloaf Hill near Hoover Dam, at an altitude of approximately 1,530 feet.

Distribution of the lake-bed remnants, indicating that prior to the deposition of the Chemehuevis the river had essentially its present grade, suggests a natural dam as the cause of the lake. The most plausible location of such a dam would be in one of the deeper canyons through which the river flows. However, the typical deposits are widespread south of the Whipple Mountains, and no canyon farther downstream appears deep enough to have served the purpose. Therefore the origin of the lake is an unsolved problem.

An elephant tooth reported from the lower part of the deposit (Newberry, 1861), and fossils from related beds in Las Vegas Valley (Longwell, 1946), date the Chemehuevis as Pleistocene though the beds cannot be dated closely within that epoch.

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COLLATE:

16 PIECES

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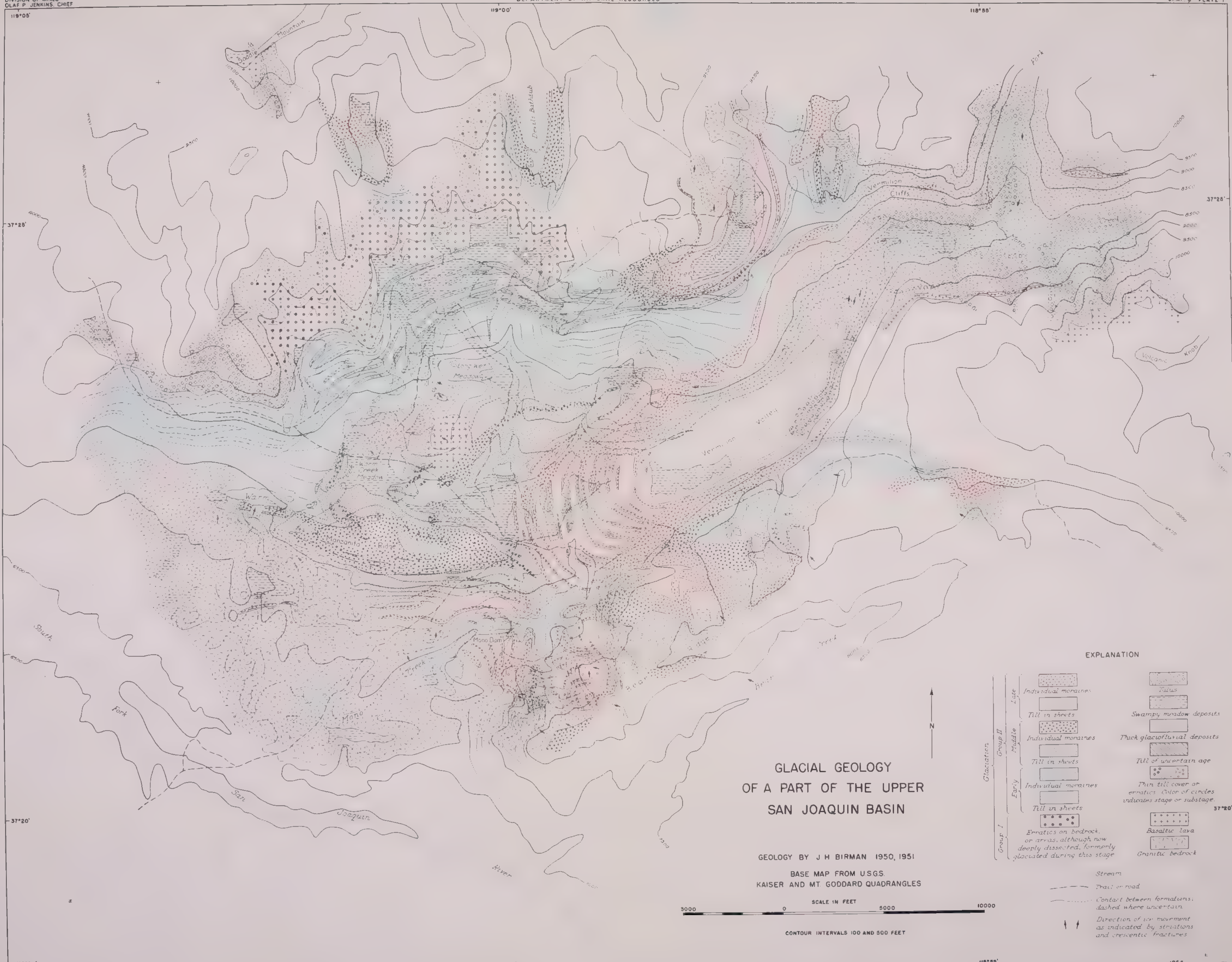
BULL 170 PART 5
CHAP 6 PLATE 1



GLACIAL GEOLOGY OF A PART OF THE UPPER SAN JOAQUIN BASIN

GEOLOGY BY J. H. BIRMAN 1950, 1951

BASE MAP FROM U.S.G.S.
KAISER AND MT. GODDARD QUADRANGLES

SCALE IN FEET
5000 0 5000 10000

CONTOUR INTERVALS 100 AND 500 FEET

EXPLANATION

Glaciation

Group II

Late
Individual moraines
Till in sheets

Middle
Individual moraines
Till in sheets

Early
Individual moraines
Till in sheets

Group I
Erratics on bedrock, or areas, although now deeply dissected, formerly glaciated during this stage

Talus

Swampy meadow deposits

Thick glaciofluvial deposits

Till of uncertain age

Thin till cover or erratics. Color of circles indicates stage or substage.

Basaltic lava

Granitic bedrock

Stream

Trail or road

Contact between formations; dashed where uncertain

Direction of ice movement as indicated by striations and crescentic fractures

1954

JTR

GEOLOGIC MAP OF THE NORTHERN PROVIDENCE MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

John C Hazzard

1953

(Surveyed 1932-1936)

SEDIMENTARY AND LAYERED VOLCANIC ROCKS

QUATERNARY
- Qal Alluvium
- Qls Landslide deposits

UNCONFORMITY

- Qt Terrace gravels

UNCONFORMITY

- Qlb Limestone breccia (age uncertain)

UNCONFORMITY

TERTIARY MIOCENE(?)
- Tvs Volcanic flows, tuffs, breccias, and associated sediments. Limestone cobble gravel locally at base

UNCONFORMITY

LOWER TRIASSIC
- Trm Moenkopi formation

UNCONFORMITY

PERMIAN PENNSYLVANIAN
- Cbs, marble Bird Spring formation

UNCONFORMITY

MIDDLE MISSISSIPPIAN (Monte Cristo limestone)
- Cyp Yellow Pine member
- Cab Anchor and Bullion members
- Cd Dawn limestone member and Basal sandstone member

UNCONFORMITY

MIDDLE DEVONIAN
- Ds, marble Sultan limestone

UNCONFORMITY

UPPER CAMBRIAN
- Cu, Cus Limestone with shale at base, formerly termed Cornfield Springs formation, see Note 4, Table 1

UNCONFORMITY (?)

MIDDLE CAMBRIAN (Bonanza King formation)
- Cbku Upper dolomite member
- Cbks, marble Silver King member
- Cbkl Lower dolomite member
- Cc Cadiz formation

LOWER CAMBRIAN
- Ccl Chambless limestone
- Cls Latham shale
- Cq Prospect Mtn. quartzite

UNCONFORMITY

PRE-CAMBRIAN
- pC Granite, gneiss, and schist (As mapped includes some younger granite)

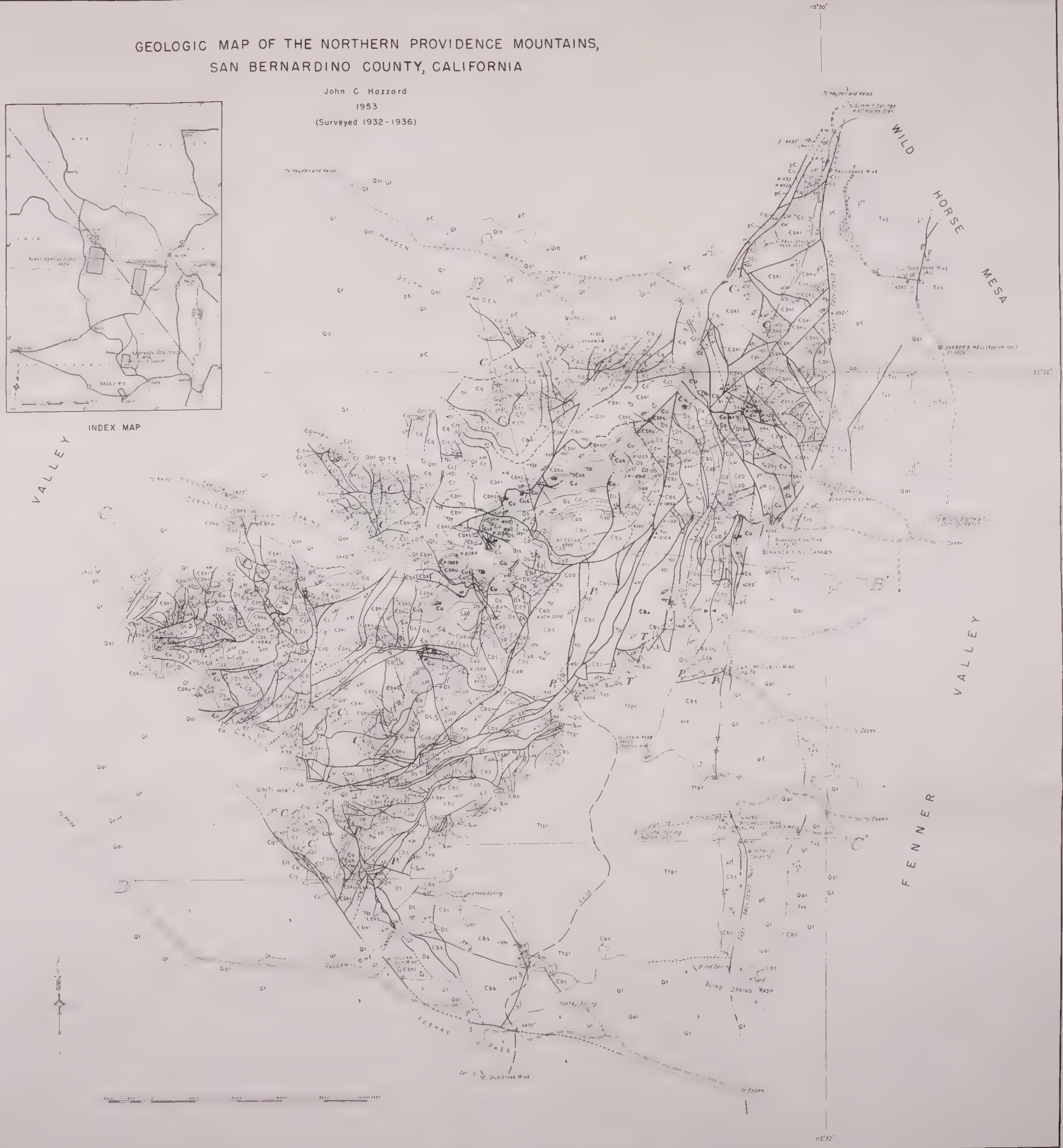
INTRUSIVE IGNEOUS ROCKS

TERTIARY MIOCENE(?)
- Tfpr Fountain Peak rhyolite (as mapped includes some pyroclastic rocks) (Note: Dike system related to rhyolite is shown on Plate 3)

POST-TRIASSIC PRE-MIOCENE(?)
- s Syenite (as mapped includes some pre-Cambrian rocks)

SYMBOLS

- Geologic boundaries
- Fault known, inferred or concealed
- Strike and dip of bedding
- Strike and dip of overturned bedding
- Strike of vertical bedding
- Axis of Syncline
- Axis of Anticline
- Mine or quarry
- Water well
- Spring
- 6800' Elevation above sea level
- P1189 Fossil locality
- Improved road
- Un-improved road
- Line of structure section
- C₁-C₂ Line of measured stratigraphic section



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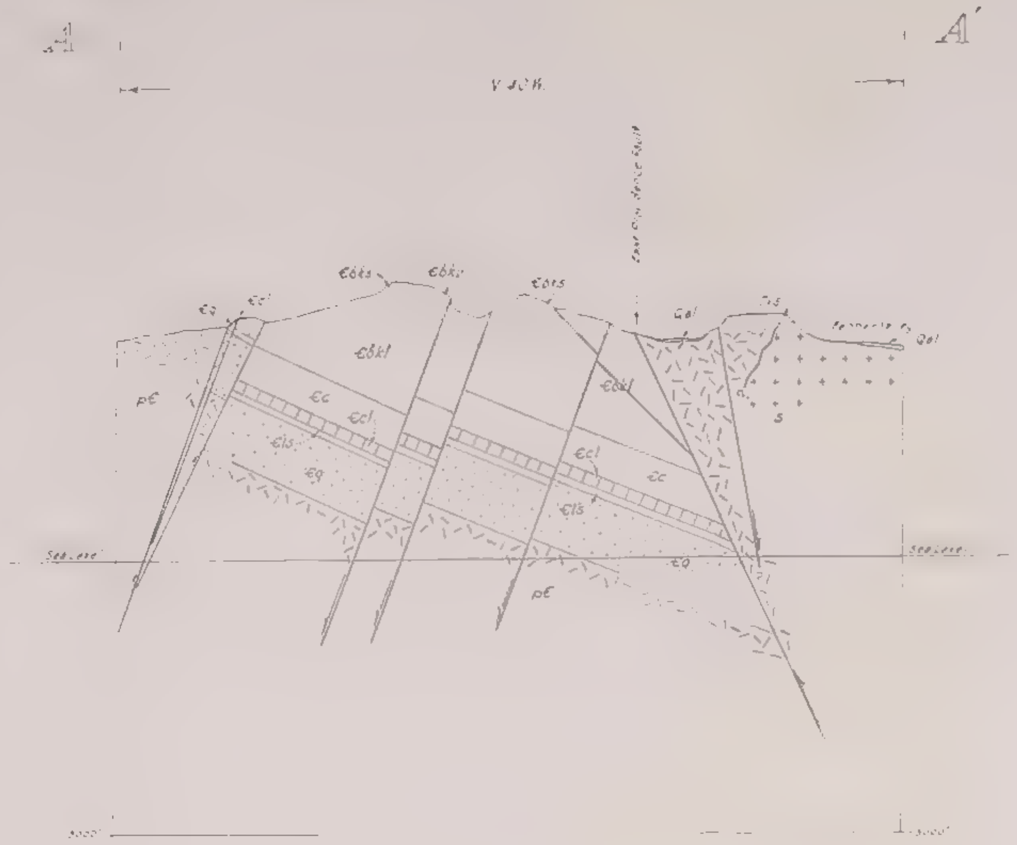

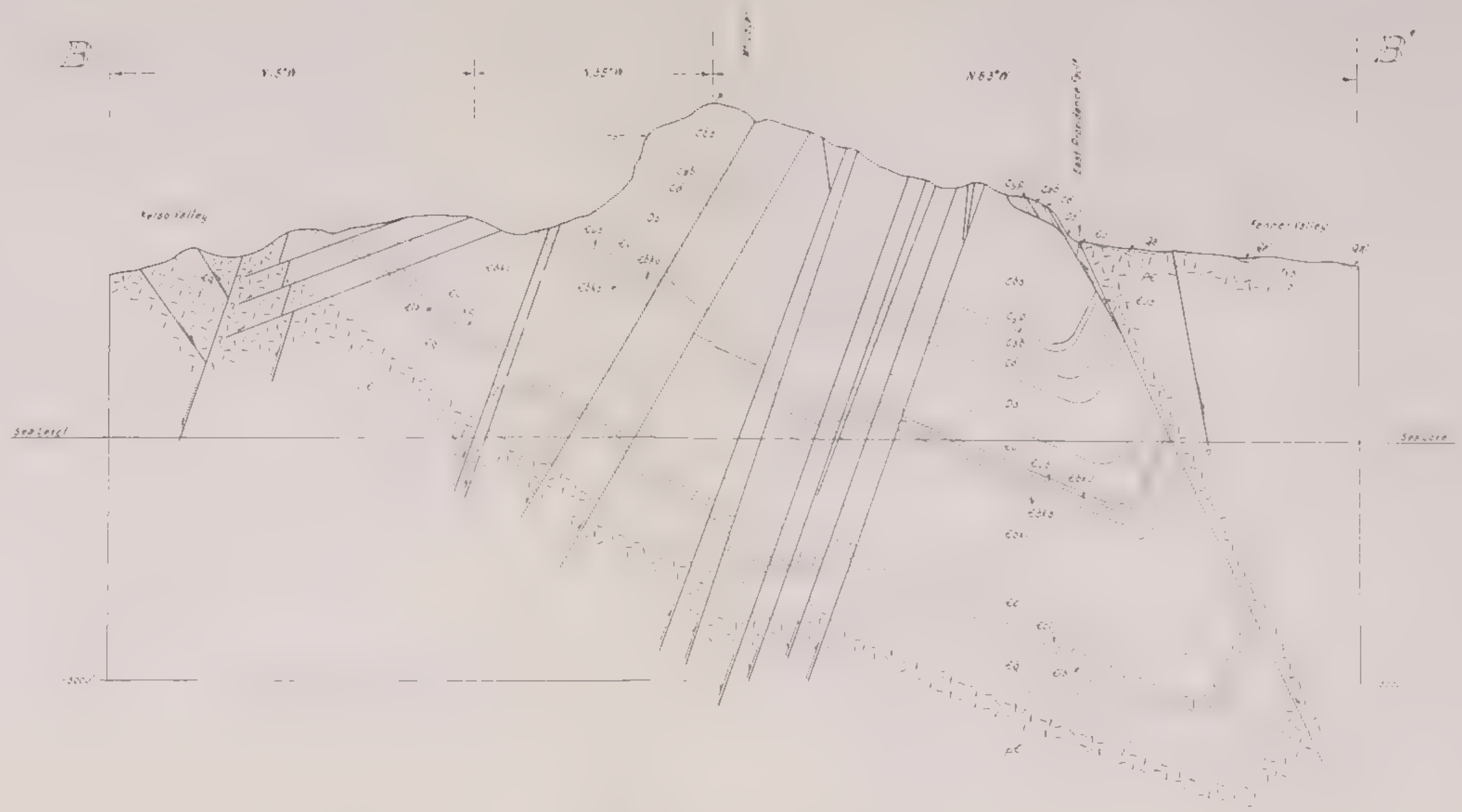

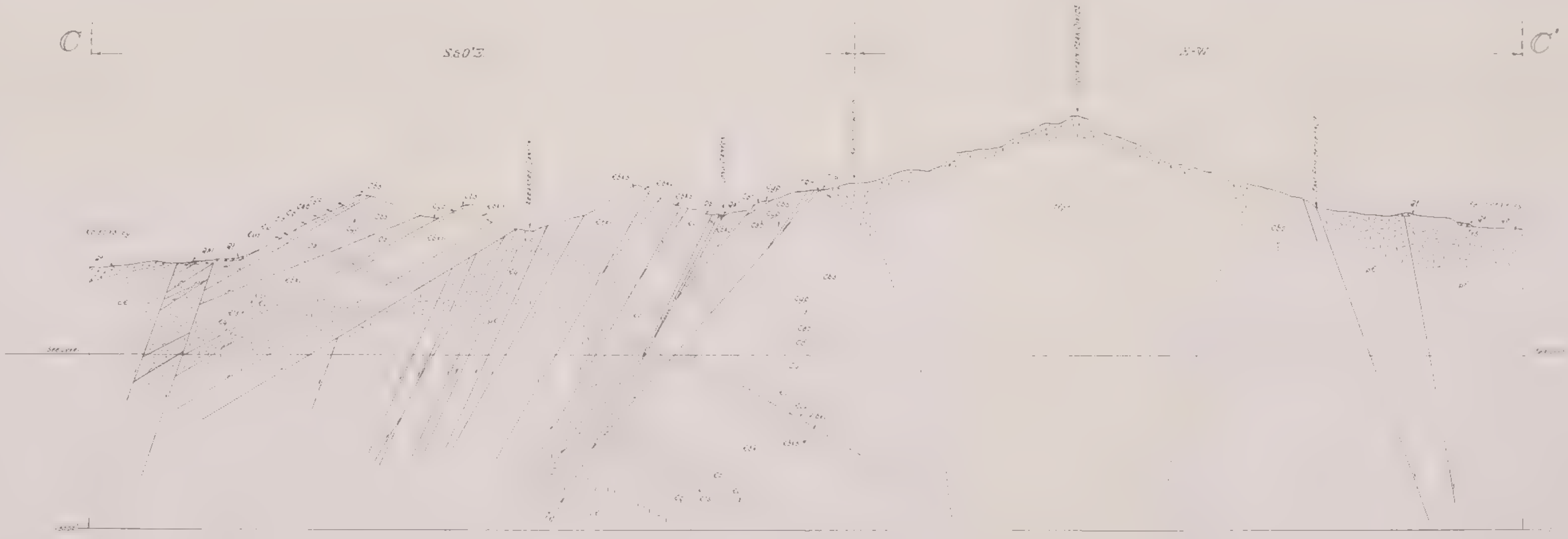

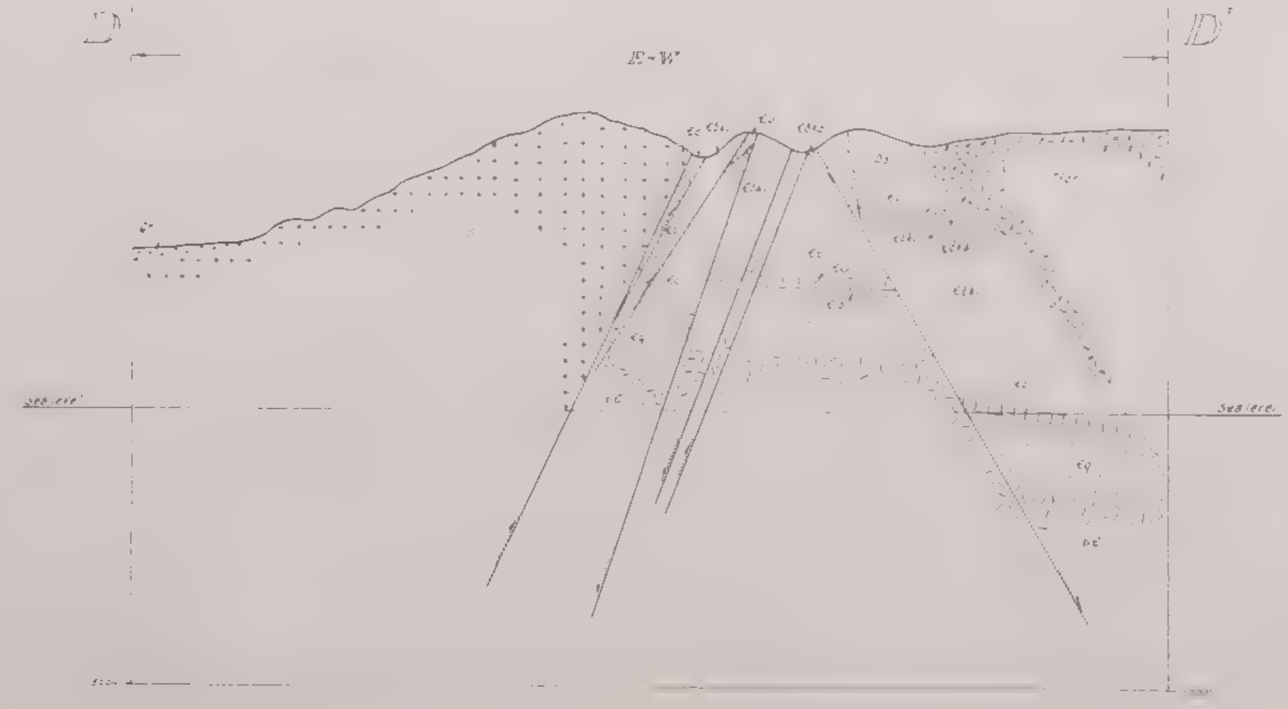

EXPLANATION

Qal: alluvium
Qt: terrace deposits } QUATERNARY

Tvs: volcanic flows, tuffs, breccias and associated sediments
Tfpr: Fountain Peak rhyolite } TERTIARY Miocene(?)

s: syenite } post-Triassic pre-Miocene(?)

Trm Moenkopi formation Lower Triassic

Cbs Bird Spring formation Permian-Pennsylvanian

Cyp: Yellow Pine member
Cab: Anchor and Bullion members
Cd: Dawn limestone and basal sandstone member } Monte Cristo limestone Middle Mississippian

Ds: Sultan limestone Middle Devonian

Ev: Dolomite with shale at base (Evs), formerly termed Cornfield Springs formation } Upper Cambrian

Ebku: Upper dolomite member
Ebks: Silver King member
Ebkl Lower dolomite member } Bonanza King fm } Middle Cambrian

Ec: Cadiz formation

Ecl: Chambless limestone
Els: Latham shale
Eq Prospect Mtn. quartzite } Lower Cambrian

pE: Granite, gneiss and schist as mapped includes some younger granite } Pre-Cambrian

SCALE
2000 1000 0 2000 4000 6000 FEET

Geology by John C. Hazzard
1951

GEOLOGIC SECTIONS OF THE NORTHERN PROVIDENCE MOUNTAINS, SAN BERNARDINO COUNTY, CALIFORNIA

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 170 CHAP IV
CONTRIBUTION 4, PLATE 4

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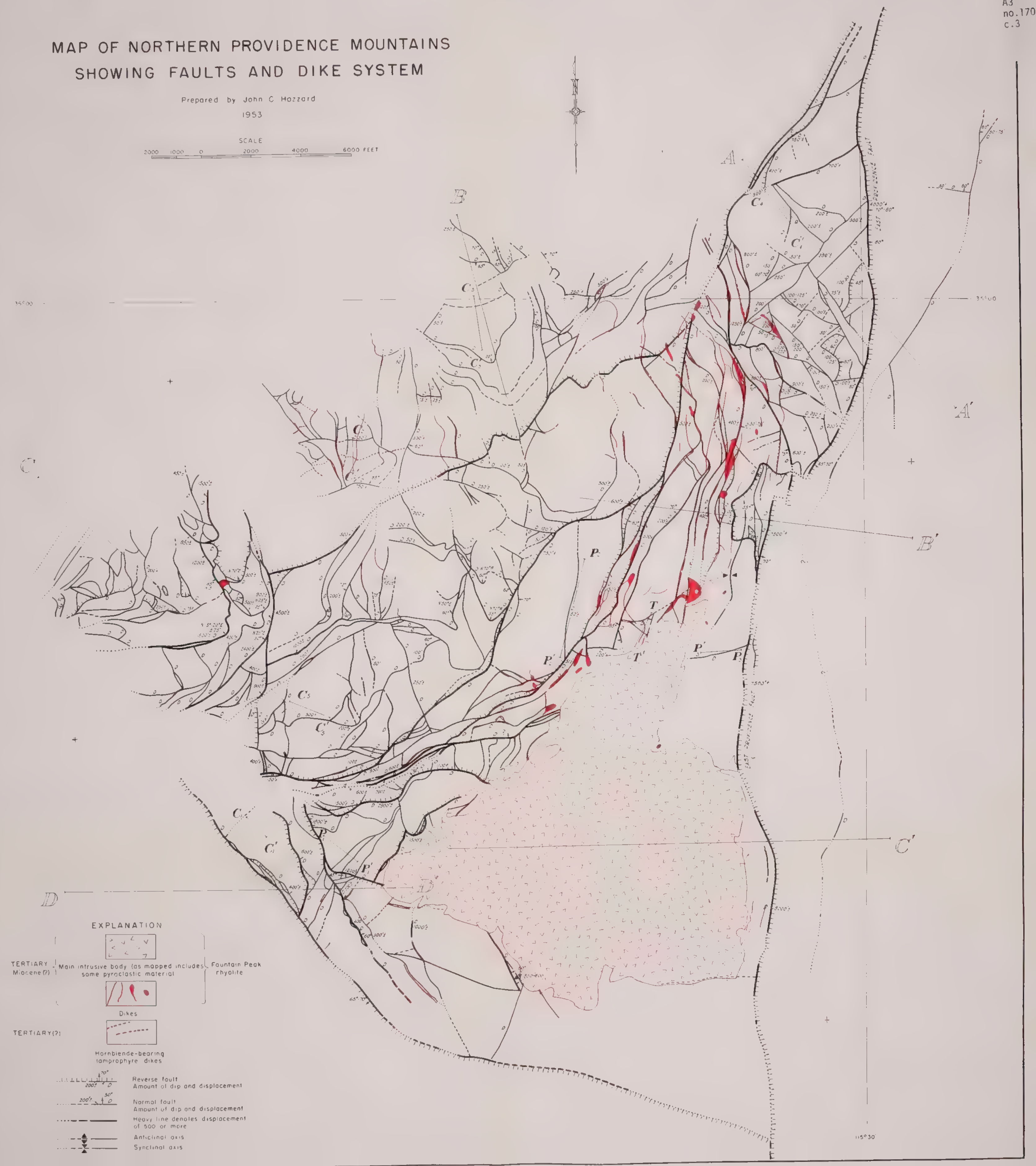
MAP OF NORTHERN PROVIDENCE MOUNTAINS SHOWING FAULTS AND DIKE SYSTEM

Prepared by John C Hazzard

1953


SCALE
2000 1000 0 2000 4000 6000 FEET
N
115°30'
35°00'
A
A'
B
B'
C
C'
D
EAST PROVIDENCE FAULT
C₁
C₁'
C₃
C₅
C₅'
P
P'
T
T'
EXPLANATION
TERTIARY
Miocene (?)
Main intrusive body (as mapped includes some pyroclastic material
Fountain Peak rhyolite
Dikes
TERTIARY (?)
Hornblende-bearing lamprophyre dikes
Reverse fault
Amount of dip and displacement
70°
200'±
D
Normal fault
Amount of dip and displacement
50°
200'±
D
Heavy line denotes displacement of 500 or more
Anticlinal axis
Synclinal axis

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BULLETIN 170, CHAPTER IV
CONTRIBUTION 5, PLATE 5

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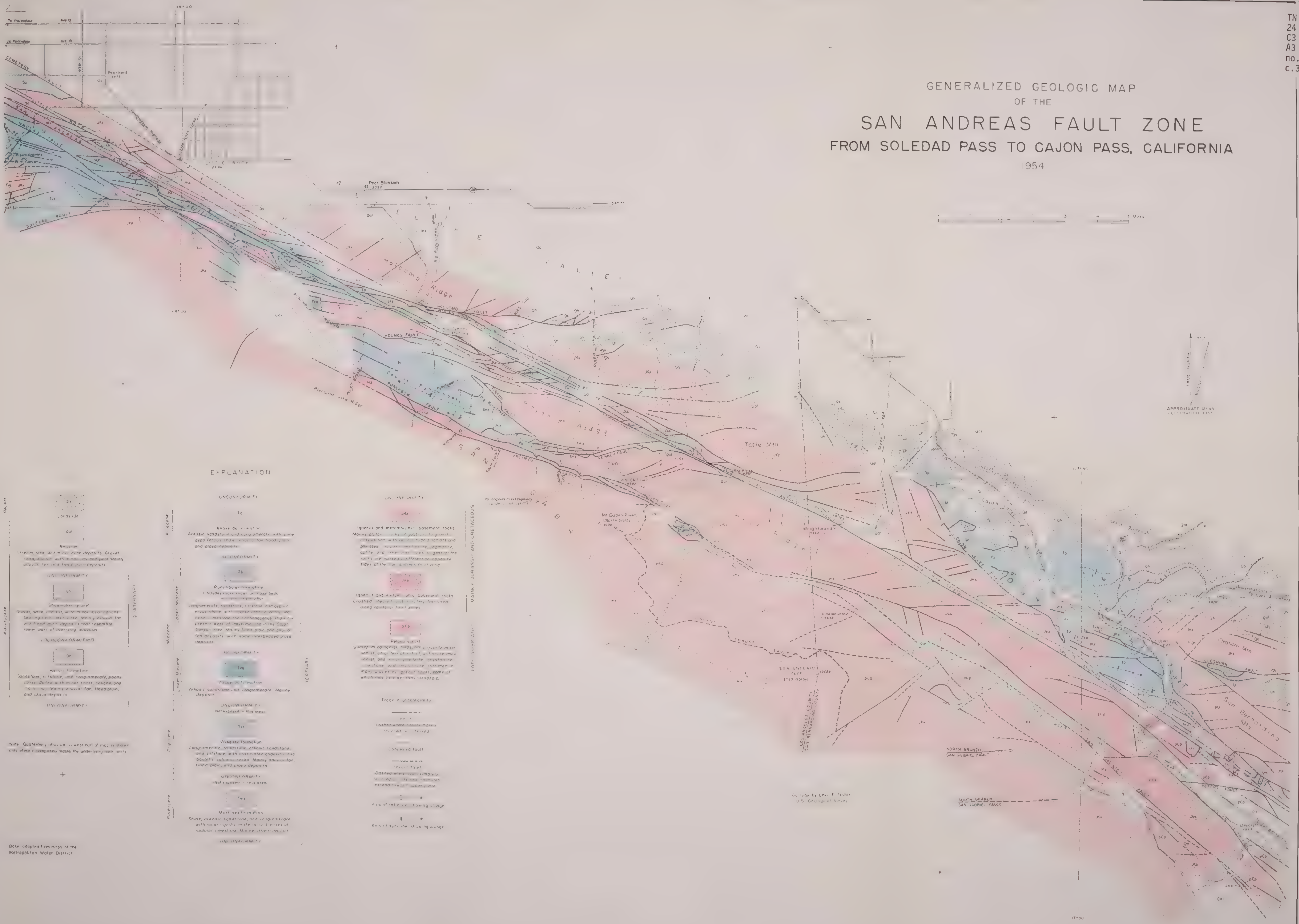
GENERALIZED GEOLOGIC MAP
OF THE

SAN ANDREAS FAULT ZONE
FROM SOLEDAD PASS TO CAJON PASS, CALIFORNIA

1954



EXPLANATION

Recent

Qls
Landslide

Qal
Alluvium
Stream, lake, and minor dune deposits. Gravel, sand, and silt with minor clay and peat. Mainly alluvial fan and flood plain deposits.

UNCONFORMITY

Pleistocene

QUATERNARY

Qs
Shoemaker gravel
Gravel, sand, and silt, with minor local caliche-bearing beds near base. Mainly alluvial fan and flood plain deposits that resemble lower part of overlying alluvium.

UNCONFORMITY(?)

Qh
Harold formation
Sandstone, siltstone, and conglomerate, poorly consolidated, with minor shale, caliche, and marly clay. Mainly alluvial fan, flood plain, and playa deposits.

UNCONFORMITY

Note: Quaternary alluvium in west half of map is shown only where it completely masks the underlying rock units.

Base adapted from maps of the Metropolitan Water District.

UNCONFORMITY

Pliocene

Ta
Anaverde formation
Arkosic sandstone and conglomerate, with some gypsiferous shale. Alluvial fan, flood plain and playa deposits.

UNCONFORMITY

Miocene

Upper Miocene

Tp
Punchbowl formation
(Includes rocks known as Cajon beds in Cajon Pass area)
Conglomerate, sandstone, siltstone, and gypsiferous shale, with coarse breccia along base. Limestone and carbonaceous shale are present west of Valyermo and in the Cajon Canyon area. Mainly flood plain and alluvial fan deposits, with some interbedded playa deposits.

UNCONFORMITY

Lower Miocene

Tvq
Vaqueros formation
Arkosic sandstone and conglomerate. Marine deposit.

TERTIARY

UNCONFORMITY
(Not exposed in this area)

Oligocene

Tvs
Vasquez formation
Conglomerate, sandstone, arkosic sandstone, and siltstone, with associated andesitic and basaltic volcanic rocks. Mainly alluvial fan, flood plain, and playa deposits.

UNCONFORMITY
(Not exposed in this area)

Paleocene

Tmz
Martinez formation
Shale, arkosic sandstone, and conglomerate with local lignitic material and lenses of nodular limestone. Marine littoral deposit.

UNCONFORMITY

UNCONFORMITY

gr
Igneous and metamorphic basement rocks
Mainly plutonic rocks of gabbroic to granitic composition, with various hybrid schists and gneisses. Includes anorthosite, pegmatite, aplite, and other dike rocks. In general the rocks are markedly different on opposite sides of the San Andreas fault zone.

grx
Igneous and metamorphic basement rocks
Crushed, sheared, and minutely fractured along faults or fault zones.

MAINLY JURASSIC AND CRETACEOUS

pCp
Pelona schist
Quartz-mica schist, feldspathic quartz-mica schist, albite-[illegible] schist, actinolite-mica schist, and minor quartzite, crystalline limestone, and amphibolite. Intruded in many places by igneous rocks, some of which may be older than Mesozoic.

PRE-CAMBRIAN(?)

Trace of unconformity

Fault
(Dashed where approximately located or inferred)

Concealed fault

Thrust fault
(Dashed where approximately located or inferred. Hachures extend toward upper plate)

Axis of anticline, showing plunge

Axis of syncline, showing plunge

Geology by Levi F. Noble
U.S. Geological Survey

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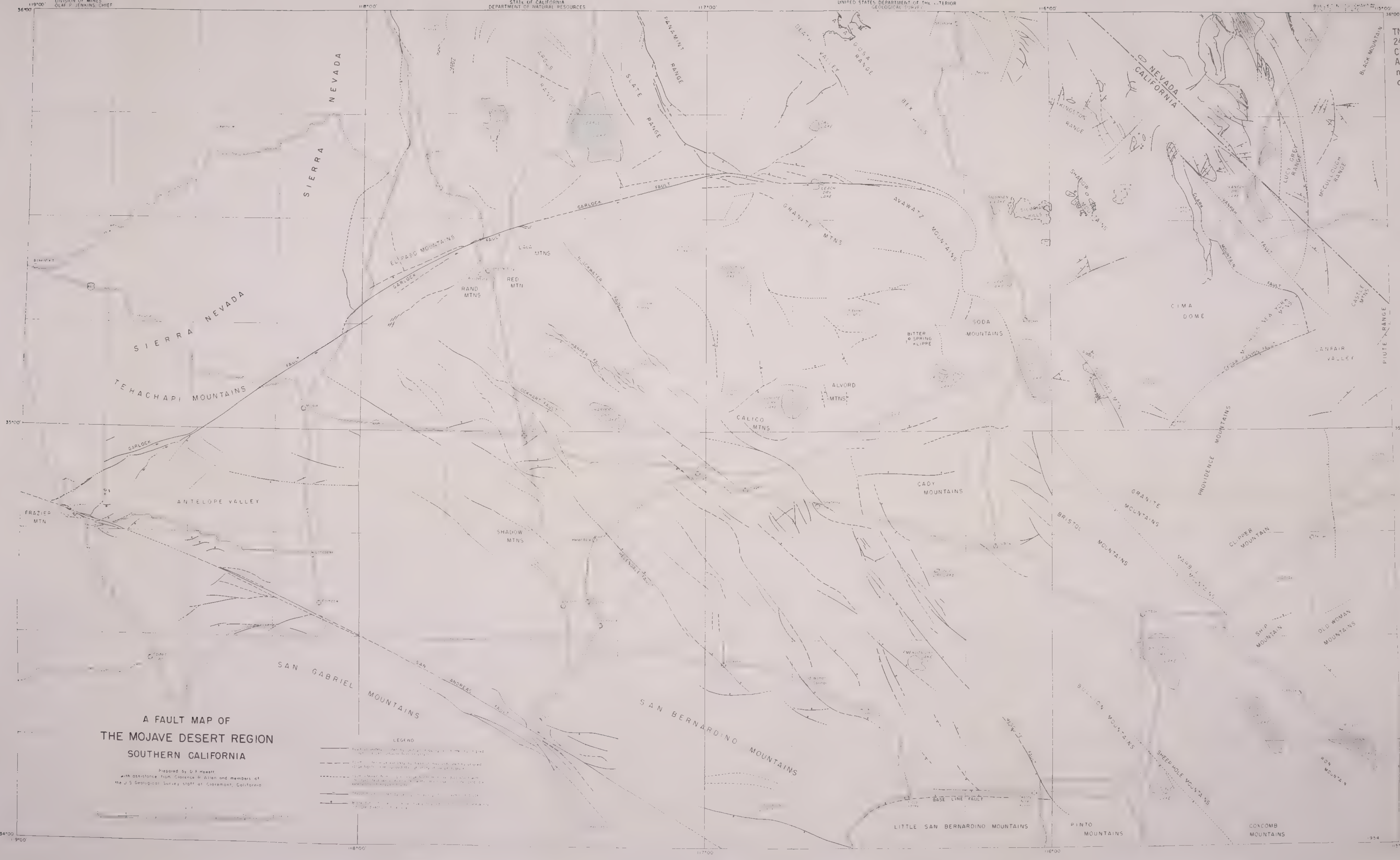

A FAULT MAP OF
THE MOJAVE DESERT REGION
SOUTHERN CALIFORNIA

Prepared by D. F. Hewett
with assistance from Clarence R. Allen and members of
the U. S. Geological Survey staff at Claremont, California

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CORRELATION CHART OF SEDIMENTARY FORMATIONS IN SOUTHERN CALIFORNIA

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BULL 170 CHAP III
CONT [illegible] PLATE

Compiled by Gordon B. Oakeshott,
Mort D. Turner, and Charles W. Jennings,
California Division of Mines, March 1954

NOTE: The authors' names that appear at the tops of the columns do not indicate responsibility for the contents of the columns (see text).

			SOUTHERN COAST RANGES			GREAT VALLEY-SIERRA NEVADA		BASIN-RANGES				MOJAVE-COLORADO DESERT			PENINSULAR RANGES			TRANSVERSE RANGES			
			Santa Maria Basin & Huasna Basin Woodring & Bramlette (50), Taliaferro (43)	Cuyama Valley [illegible] (52), Beck (52), Schwade (54)	Reef Ridge-Kettleman Hills Woodring et al (40), Stewart (46)	S. San Joaquin Valley Hoots, et al (50), Dibblee (unpub)	S. Sierra Nevada Miller & Webb (40), Durrell (40), Dibblee (unpub)	El Paso Mountains Dibblee (52), Hulin (25)	Inyo Range Kirk (18), Bateman (54), Phleger (33), Merriam (54)	Death Valley [illegible]	Nopah-Resting Spgs Mts Hazzard (37, 51), Mason (48), Merriam (54)	Providence Mountains Hazzard & Mason (36), [illegible] (54)	Barstow Area Bowen (54), Miller (44), Dibblee (Unpub), McCulloh (54)	Imperial Valley Tarbet (51), Dibblee (54), Durham (54), Longwell (54)	Coastal San Diego and Orange Cos. Woodford [illegible], Hanna (26), Hertlein & Grant (44), Ellis & Lee (19)	Santa Ana Mts & Puente Hills Woodring & Popenoe (45), Richmond (5?), Moran (54), Woodford (54), [illegible] (51)	Los Angeles Basin-Palos Verdes Hills Schoellhamer & Woodford (51), Woodford (54), Woodring, Bramlette & Kew (46)	Santa Monica Mountains Hoots (31), Durrell (54)	E. Ventura Basin (Soledad & San Fernando Basins) Jahns (39, 40), Kew (24), Miller (34), Oakeshott (50, 54), Winterer & Durham (54)	Ridge Basin Eaton (39), Crowell (52, 54)	Central Ventura Basin Putnam (42), Bailey (54), Bishop (54)	Santa Ynez Mountains Woodring, et al (45), Dibblee (50), Page, et al (51)
QUATERNARY	Pleistocene	Upper	Terrace deposits Orcutt sand	Fanglomerate	Older alluvium	Fanglomerate and terrace gravels	Fanglomerate and terrace gravels	Terraces	Fanglomerate moraines, and lake beds	Fanglomerate and lake beds	Gravel beds and	Fanglomerate	Older alluvium	Lake Coahuila deposits Chemehuevis lake beds	Lacustrine and terrace deposits Bay Point formation Palo cg	Terrace deposits	Marine and non-marine terrace deps Palos Verdes sd	Alluvial plain and marine terrace deposits	Terrace deposits	Fanglomerate and terrace	Terrace deposits and older alluvium	Terrace deposits Marine terraces
		Lower	Paso Robles formation	Paso Robles formation	Tulare formation	Tulare Kern River	Kern River	Ricardo	Older moraines, fanglomerate, and lake beds	Fanglomerate and lake beds	lake beds		lake beds		Temecula arkose	La Habra Marine ?	San Pedro sd Timms Pt silt Lomita marl	Marine conglomerate	Saugus fm	deposits	San Pedro fm (Marine "Saugus", Las Posas) Santa Barbara	Casitas fm
TERTIARY	Pliocene	Upper	Careaga fm Foxen fm		San Joaquin fm Etchegoin fm	fm formation	formation	formation	"Tertiary"	Funeral fanglomerate	China Ranch beds	"Late Tertiary"		Borrego fm Marine	Sweitzer fm San Mateo fm	"Pico" fm	"Pico" fm	Pico	Sunshine Ranch mbr cg - ss mbrs	Hungry Valley formation	fm Mud pit sh (Pico stage)	Santa Barbara fm
		Lower	Sisquoc fm	Morales fm	Jacalitos fm	Chanac Etchegoin fm formation	Chanac Etchegoin fm formation		lake beds	Greenwater volcanics	Volcanic seds	volc and seds	Lake beds in [illegible] Hills	Palm Spring fm Imperial fm	San Diego fm	Repetto fm	Repetto fm	(San Diego) fm	Towsley fm Repetto fm Pico fm siltst mbr	Peace Valley beds Violin breccia	Pico fm (Repetto stage)	
	Miocene	Upper	Sta Margarita fm	Santa Margarita fm Quatal fm	Monterey fm Reef Ridge sh	Sta Margarita fm	Sta Marg. fm Fruitvale sh			Furnace Creek fm	Furnace Creek fm (?)		Barstow fm	Alverson Canyon formation	Capistrano fm Monterey fm	Puente fm Sycamore Canyon mbr Yorba sh mbr Soquel ss mbr La Vida sh mbr	(Puente) Malaga mudst mbr Valmonte diatomite mbr	Modelo fm	Elsmere mbr Modelo Mint Canyon fm	Mint Canyon fm Castaic	Santa Margarita fm Monterey (Modelo)	Sisquoc fm
		Middle	Monterey fm Point Sal fm	Monterey fm [illegible] Creek Caliente fm	McLure sh	Maricopa or Monterey fm Bena gravel	Monterey or Maricopa Round Mountain silt Bena gravel						"Calico" fm	Split Mt fm	San Onofre brec Topanga (Temblor) fm	Topanga fm	Monterey fm Altamira sh mbr	Topanga fm	formation Tick Canyon fm	formation	fm Topanga fm	Monterey formation
		Lower	Vaqueros fm	Painted Rock sd Soda Lake sh	Temblor fm	Temblor or Vaqueros	Temblor or Vaqueros Olcese sd Freeman silt Jewett & Pyramid Hill sd			Artist Drive				Marine	Vaqueros fm	Vaqueros		Vaqueros fm	Topanga (?) fm		Rincon fm Vaqueros fm	Tranquillon volc Rincon sh Vaqueros fm
	Oligocene		Lospe fm Sespe fm	Simmler fm		Pleito fm Tecuya fm	Walker fm Bealville fang	Goler fm		fm Titus Canyon fm					Sespe fm	Sespe fms		Sespe fm	Vasquez fm		Sespe fm	Sespe fm Alegria fm
	Eocene	Upper			Kreyenhogen sh	San Emigdio fm Reed Canyon sh Metralla ss									Poway cg Marine						Coldwater ss Cozy Dell sh Matilija ss	Gaviota fm Matilija ss
		Middle		Unnamed Eocene beds	Avenal ss	Tejon fm Live Oak sh Uvas ss-cg									La Jolla fm Rose Canyon sh Torrey sd	Santiago fm			Domengine "fm"		(Las) Llajas fm Juncal fm	Anita sh Juncal fm Sierra Blanca ls
		Lower													Delmar sd						Santa Susana fm	
	Paleocene		?												Silverado fm	Silverado fm Non-marine mbr		Martinez fm	"Martinez fm"	"Martinez fm"	Martinez fm	
CRETACEOUS		Upper	Asuncion (?) gp Pacheco (?) gp	Unnamed	Panoche fm										"Chico fm"	Williams fm Ladd fm Trabuco fm		"Chico fm" Trabuco fm			Chico fm	Jalama fm
		Lower	"Shasta" gp	Cretaceous beds																		Espada fm
JURASSIC			Knoxville fm Franciscan fm	Franciscan-Knoxville gp	Franciscan gp			Quartzite							Black Mt volc and	Santiago Peak volc	(Franciscan gp ?) Catalina					Honda fm Franciscan fm
TRIASSIC							(Kaweah series) Kernville series	cg	sh, tuff, qtzite, crystalline ls			Moenkopi fm ?	Lake-bed chert and tuff in Sidewinder series		metased	Bedford Canyon (Santa Ana) fm	schist	Santa Monica sl				
PERMIAN						?		Garlock series	Reward cg Owenyo ls	ls		Mt Edgar ls	Fairview Valley fm			?				?		
PENNSYLVANIAN						Crystalline	Crystalline		ls, sh, ss	Tihvipah ls Rest Spring sh	Bird Spring ls Lampasas (?) series	Bird Spring ls Providence Mts ls	Tuffs in Hodge volc Oro									
MISSISSIPPIAN						limestone and	limestone and		White Pine gp Tin Mountain ls	Perdido fm Tin Mountain ls	Monte Cristo ls Yellowpine ls Bullion ls Anchor ls Dawn ls (L)	Monte Cristo ls Yellowpine ls Bullion dol Anchor ls Dawn ls Basal Qtzite	Grande series	Crystalline limestone	Metased	Crystalline limestone			Placerita series	Crystalline limestone		
DEVONIAN						quartzite	quartzite		ls, dol, ss	Lost Burro fm	Sultan ls Crystal Pass ls Valentine ls Ironside dol (M) Dol Basal ss	Sultan ls Crystal Pass ls Valentine ls Ironside dol Dol Basal ss		and various metased		and various metased				and various metased		
SILURIAN									ls, dol, qtzite	Hidden Valley dol	(M) dol											
ORDOVICIAN								?	Ely Springs dol Eureka qtzite Barrel Spring fm Mazourka fm	(U)-Ely Springs dol (M)-Eureka qtzite (L)-Pogonip ls	(U)-Ely Springs dol (M)-Eureka qtzite (L)-Pogonip (?) dol											
CAMBRIAN									ss, ls, sh (L) Silver Peak gp Campito ss	(U)-Nopah fm (M)-Racetrack dol (L)-Noonday dol	(U) Nopah fm Cornfield Springs fm (M) Bonanza King fm Silver King dol Cadiz fm Wood Canyon fm Zabriskie qtzite Stirling qtzite	Cornfield Springs fm (M) Bonanza King fm Silver King dol Cadiz fm (L) Stirling qtzite										
PRE-CAMBRIAN								Mesquite schist and Rand schist	Deep Spring fm Reed dol	Pahrump series Kingston Pk fm Beck Spring dol Crystal Spring fm Qtzite, schist, and gneiss	Pahrump series Kingston Pk fm Beck Spring dol Crystal Spring fm	Schist, gneiss, marble		Schist		?			Pelona schist	Pelona schist		

EXPLANATION

- - - ? - -
Boundary between geologic units

Unconformity

Horizontal gradation and lensing

Boundary between geologic ages

Non-marine

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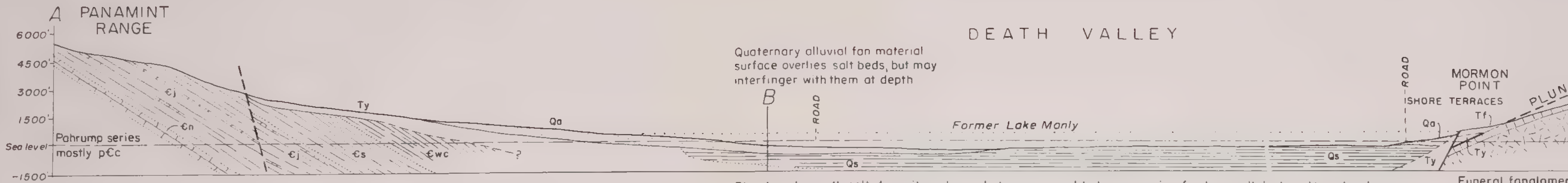
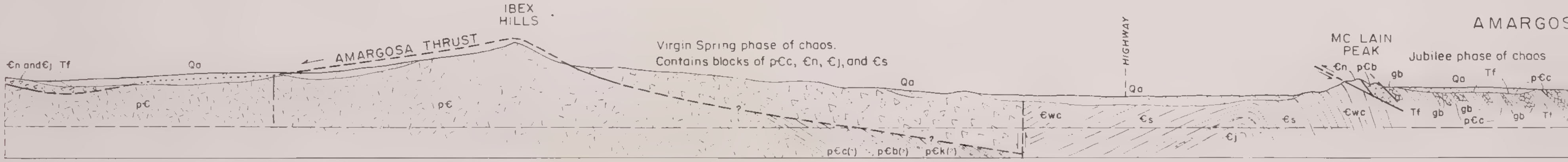


Quaternary alluvial fan material surface overlies salt beds, but may interfinger with them at depth

Section is diagrammatic here. Structure of the Paleozoic rocks actually is much more complex than shown. All formations dip toward Death Valley

Structure beneath salt deposits unkown, but is assumed to be a mosaic of sub-parallel, steep to vertical faults that constitute the Death Valley strike-slip fault zone.

Funeral fanglomer
Younger Tertiary v
rocks which in tur
thrust on a fault c
erate is in deposi



Virgin Spring phase of chaos. Contains blocks of p€c, €n, €j, and €s

Jubilee phase of chaos

Autochthonous Pahrump series(?)

Quaternary	Qa	Alluvial fan deposits
	Qs	Alternating beds of rock salt and clay (Death Valley)
Plio-Pleistocene(?)	B Tf	Funeral fanglomerate *(In upper half of section, fanglomerate and some volcanic ash with interbedded basalt flow, B.* *In lower half of section, clay shale, siltstone, fanglomerate, and some volcanic ash, interbedded with megabreccia.)*
Younger Tertiary	Ty	Undifferentiated sedimentary rocks *(Fanglomerate, conglomerate, breccia, shale, sandstone, fresh-water limestone, and volcanic ash.)* Undifferentiated volcanic rocks *(Chiefly rhyolite, andesite, and tuff)*

E

Lower Cambrian	€wc €s €j €n
Pahrump series (later pre-Cambrian)	p€k p€b p€c

CROSS SECTION OF DEATH VALLEY REGIO

Along A–B–C–D (Pl.7). The part of the section marked A-B shows the generalized geologic st

TN
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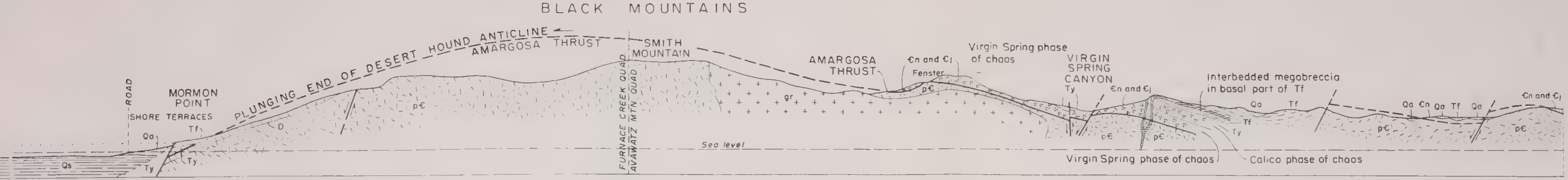
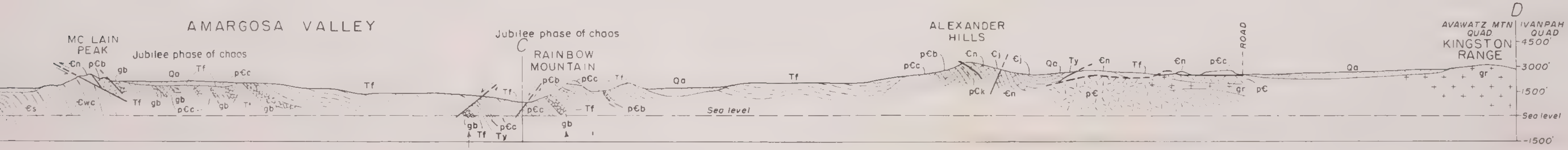
C3
A3
no.17
c.3



el, steep to vertical

Funeral fanglomerate conformably overlies Younger Tertiary volcanic and sedimentary rocks which in turn overlie the Amargosa thrust on a fault contact Funeral fanglomerate is in depositional contact with pЄ.



Megabreccia lenses composed of various pre-Funeral rocks (mostly of the Pahrump series) and interlayered with Tertiary sedimentary rocks of undetermined age. Furnace Creek fault zone beneath here? (Recurrent faulting; largely pre-Funeral fanglomerate)

EXPLANATION

h Valley)

some
B
fanglomerate,
gabreccia)

e, sandstone,

Lower Cambrian
- Єwc Wood Canyon formation *(Quartzite, shale, and fossiliferous limestone)*
- Єs Stirling quartzite
- Єj Johnnie formation *(Quartzite, shale, and dolomite)*
- Єn Noonday dolomite

Pahrump series (later pre-Cambrian)
- pЄk Kingston Peak formation *(Conglomerate, quartzite, and shale)*
- pЄb Beck Spring dolomite
- pЄc Crystal Spring formation *(Quartzite, shale, dolomite, and intrusive diabase)*

Earlier pre-Cambrian
- pЄ Basement complex of metamorphic rocks *(Chiefly granitic and dioritic gneiss)*

Post-Triassic
- gr Intrusive granite
- gb Brecciated granite and granite porphyry *(Megabreccia)*

- D Altered dolomite (marble) and quartzite at Mormon Point *(Relations unknown; age pЄ(?))*

- Chaos

0 1 2 3 Miles

VALLEY REGION FROM PANAMINT RANGE TO KINGSTON RANGE

-B shows the generalized geologic structure across the Virgin Spring area The part of the section from B to D is modified from Noble (1941)

TN
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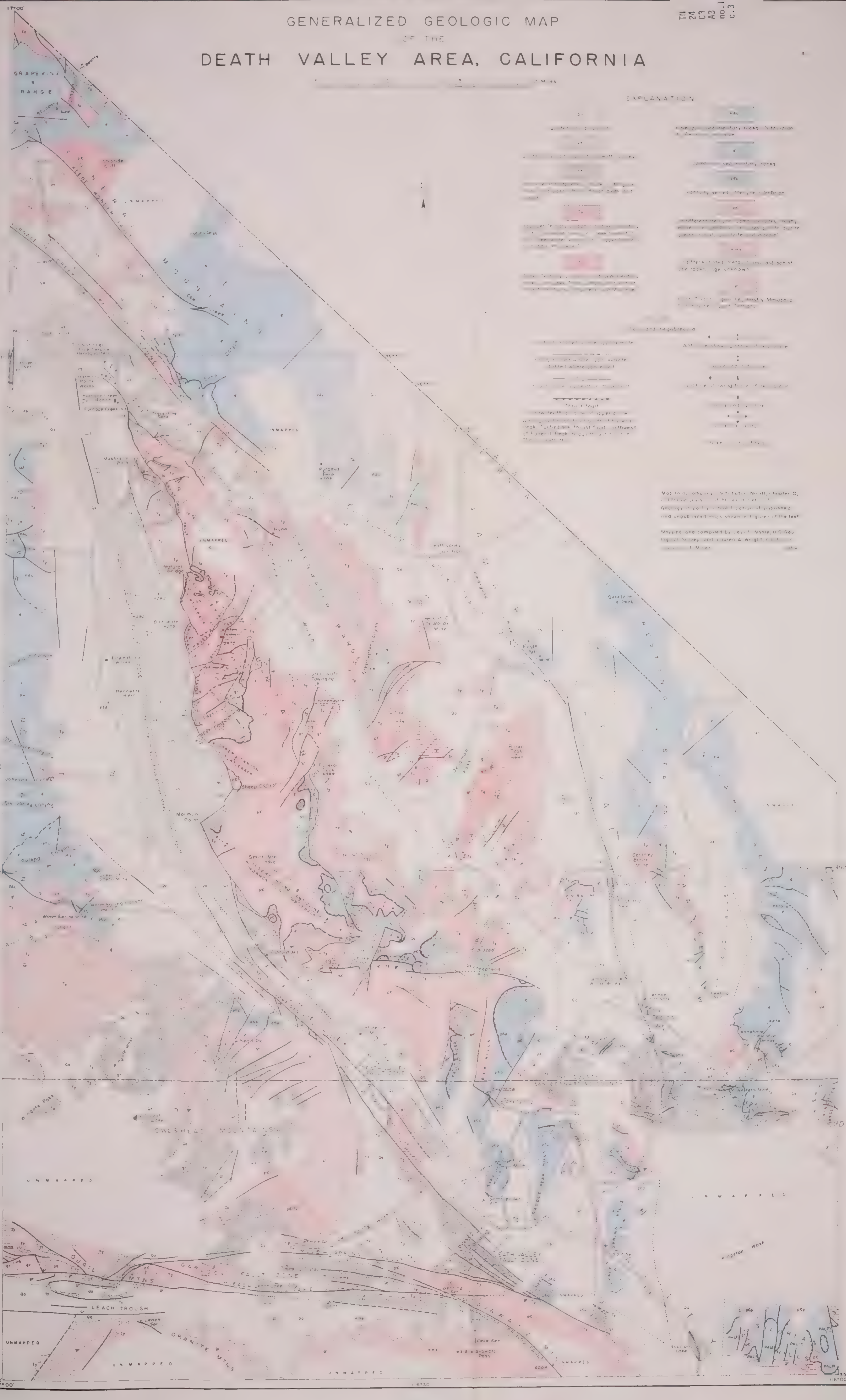
A3
no.170
c.3

GENERALIZED GEOLOGIC MAP
OF THE
DEATH VALLEY AREA, CALIFORNIA



Map to accompany Contribution No. 10, Chapter II, California Division of Mines Bulletin 170. Geology is partly a modification of published and unpublished maps shown in figures of the text.

Mapped and compiled by Levi F. Noble, U.S. Geological Survey, and Lauren A. Wright, California Division of Mines 1954

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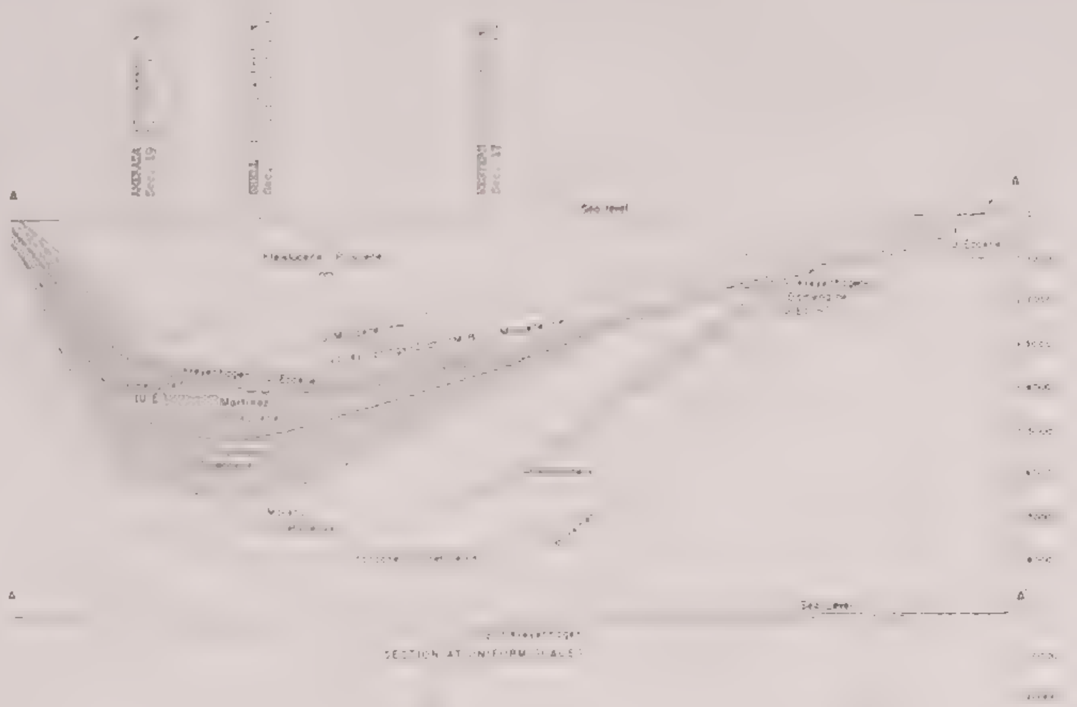
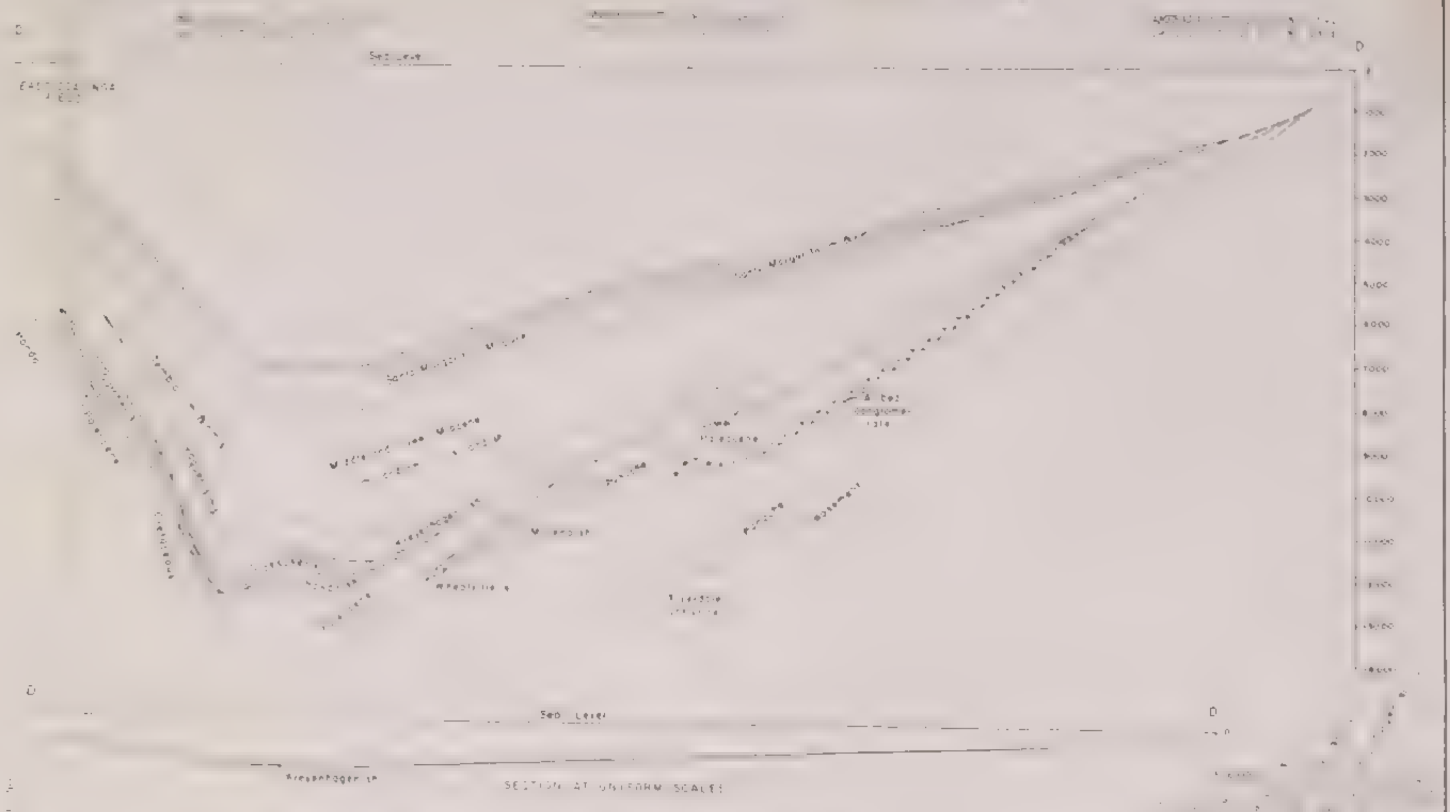
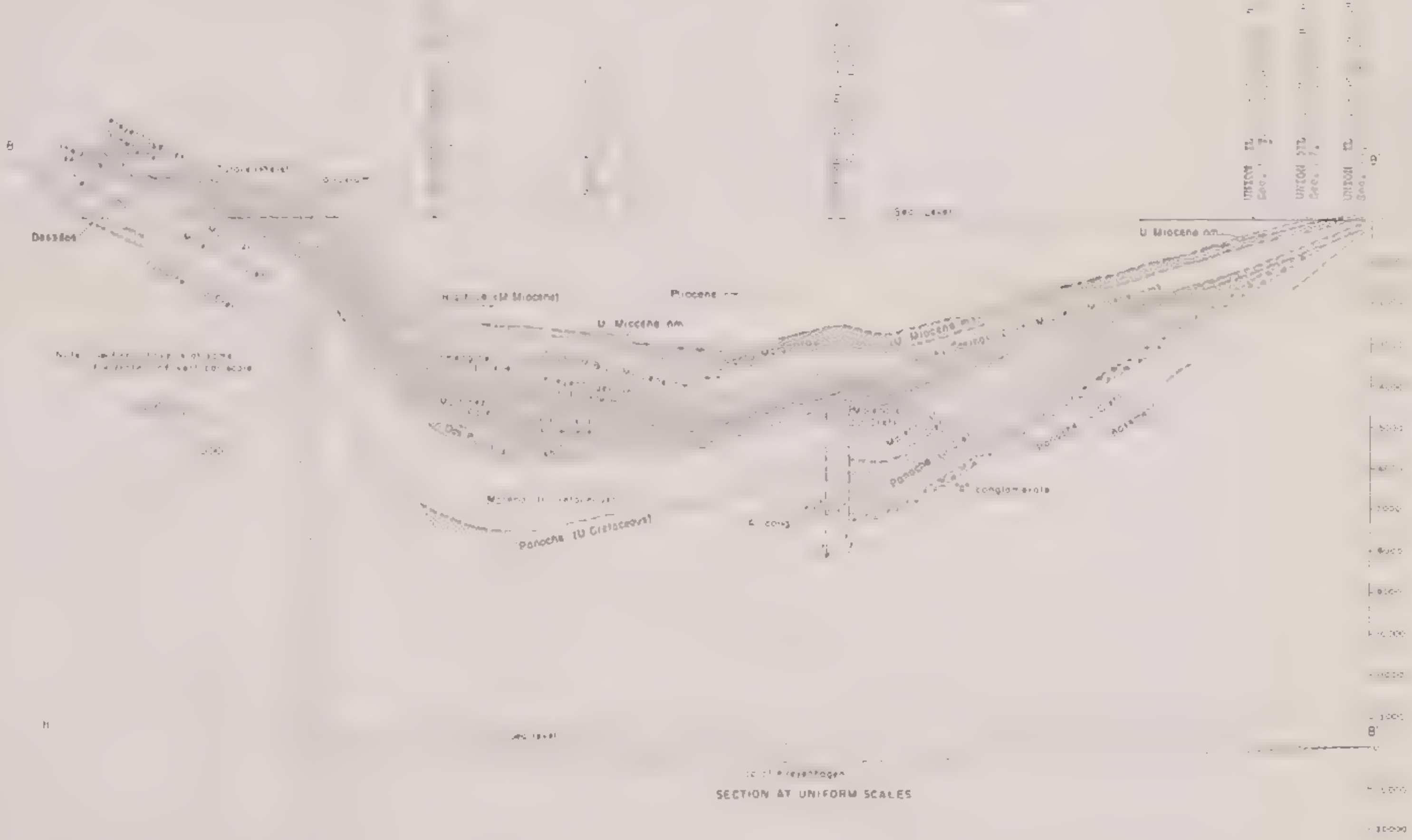
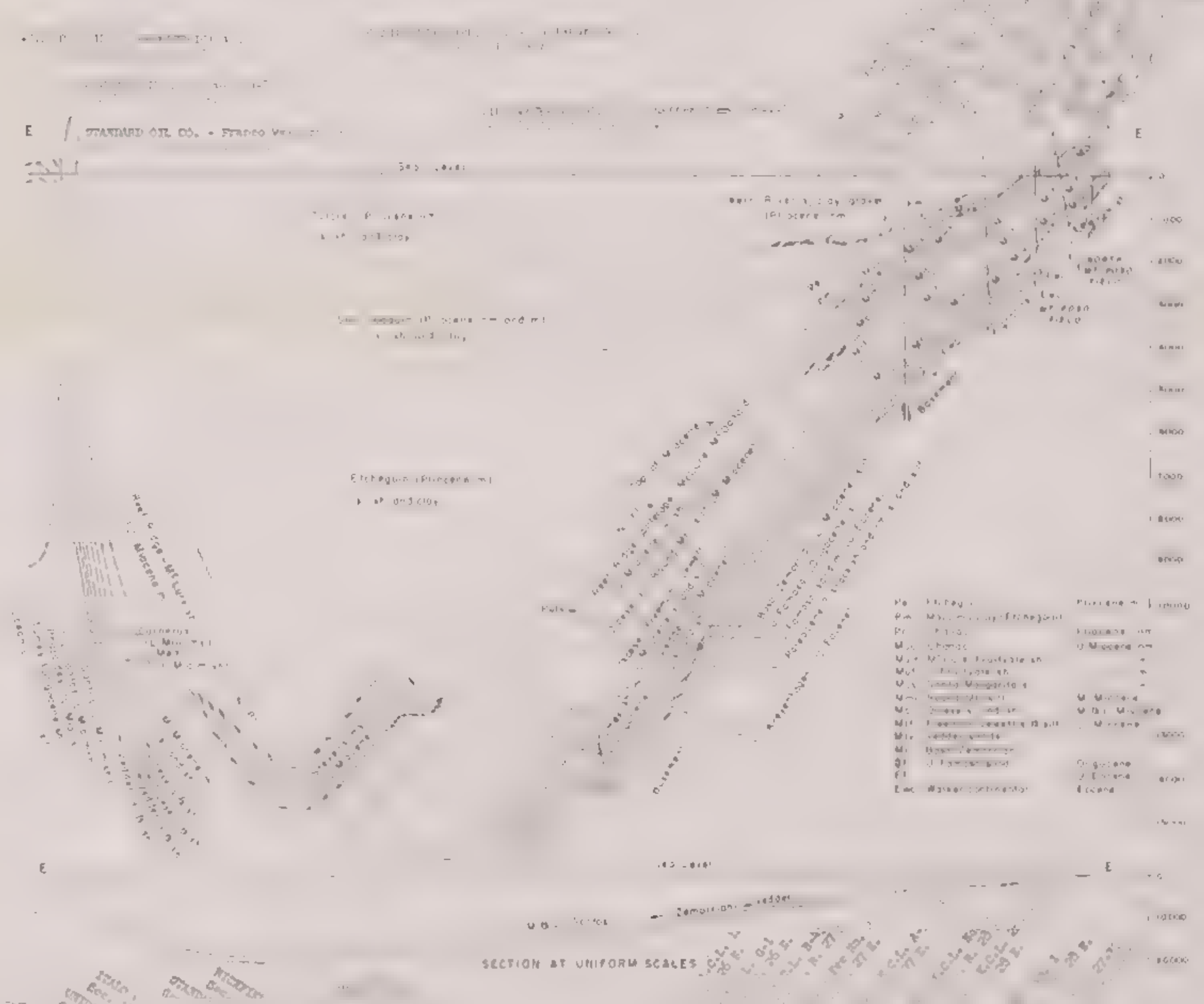
DEPARTMENT OF NATURAL RESOURCES

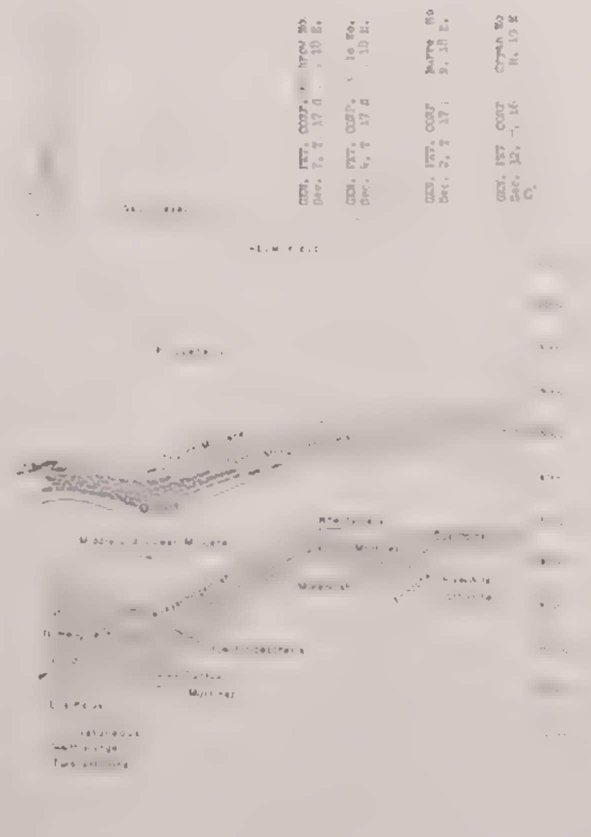
BULLETIN 170, CHAPTER II
CONTRIBUTION 8, PLATE 6







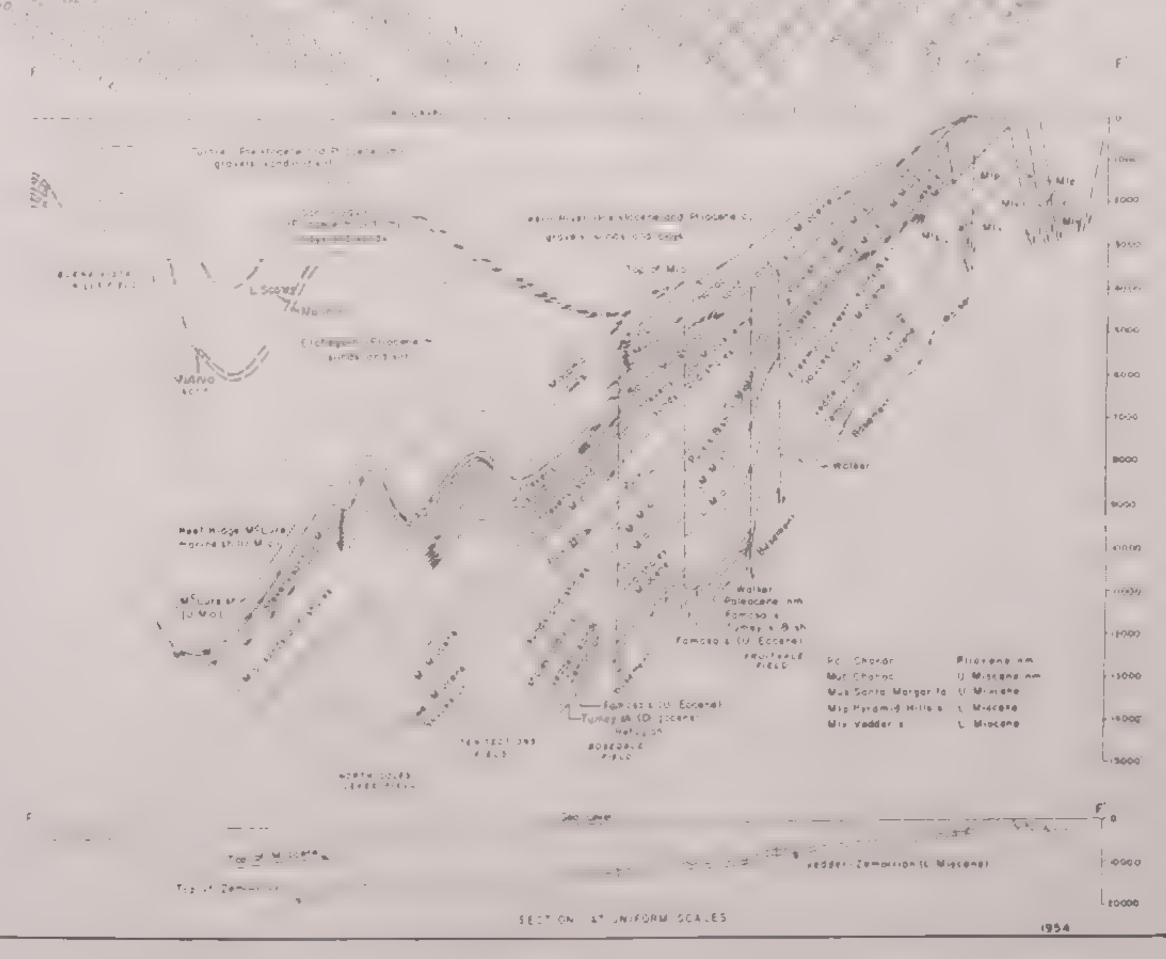




STRUCTURE SECTIONS ACROSS SOUTHERN SAN JOAQUIN VALLEY

0 20,000 40,000 FEET

HORIZONTAL SCALE



EXPLANATION

c	conglomerate
nm	nonmarine
m	marine
ms	marine sand
msh	marine shale
mssh	marine sand and shale
s	sand

1954

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24
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no. 170
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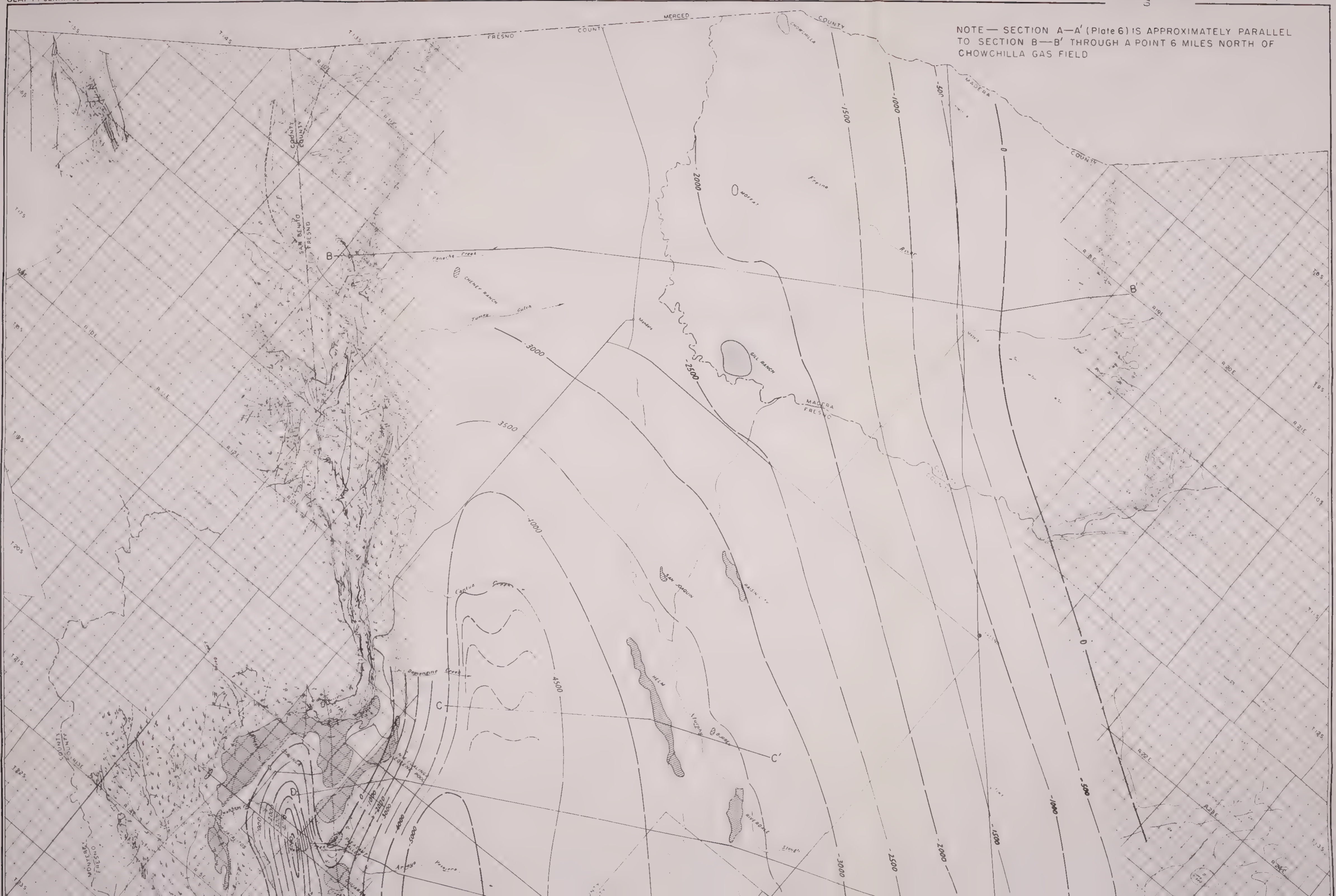
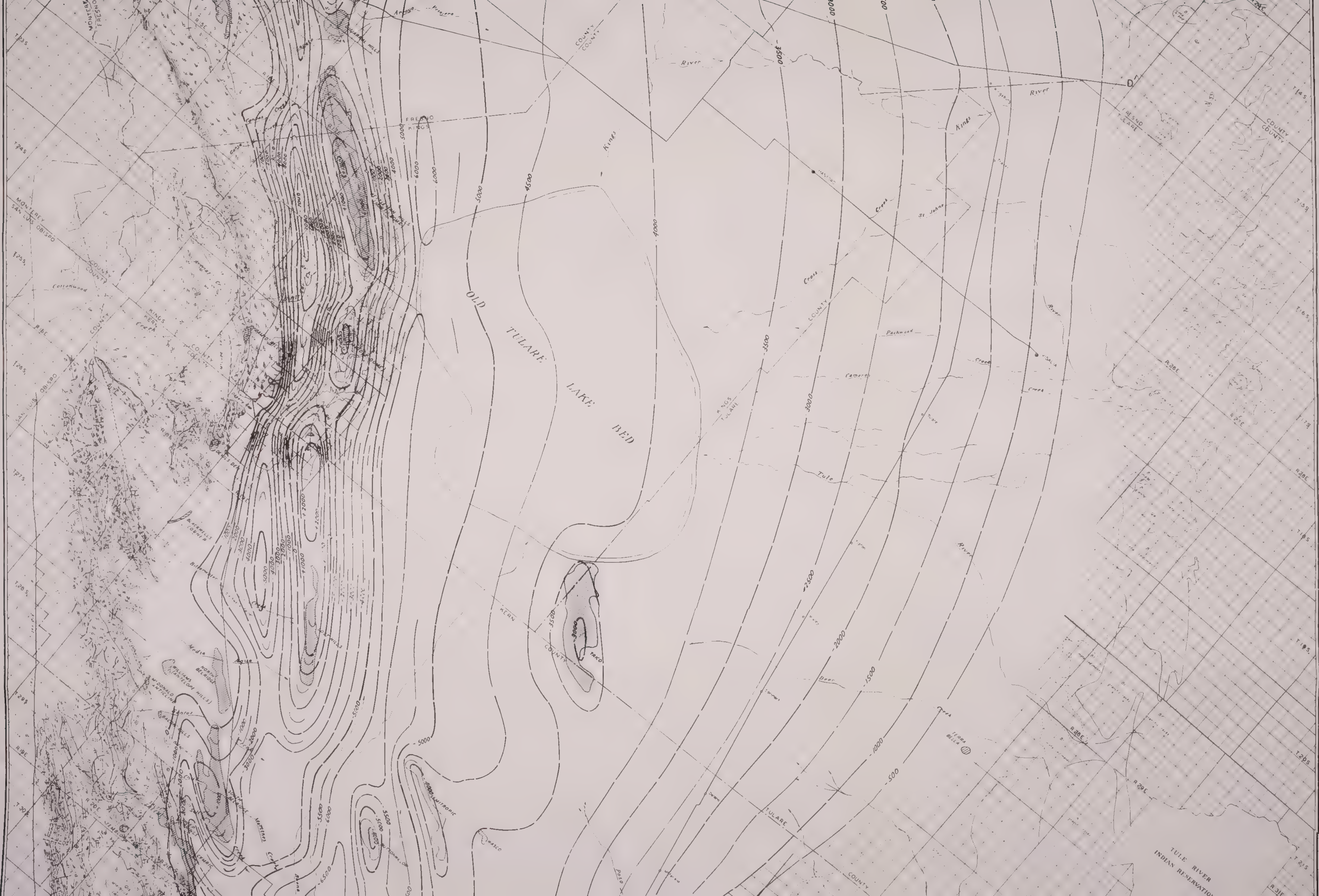


NOTE — SECTION A—A′ (Plate 6) IS APPROXIMATELY PARALLEL TO SECTION B—B′ THROUGH A POINT 6 MILES NORTH OF CHOWCHILLA GAS FIELD


MONTEREY
FRESNO
SAN LUIS OBISPO
KINGS
COUNTY
FRESNO
KINGS
KINGS
TULARE
KERN
COUNTY
TULARE
COUNTY
OLD
TULARE
LAKE
BED
Kings
River
Cross
Creek
St Johns
Packwood
Cameron
Creek
Tule
Deer
Creek
TERRA
BELLA
Poso
Cottonwood
Creek
Bitterwater
TULE RIVER
INDIAN RESERVATION
T 23 S
T 24 S
T 25 S
T 26 S
T 27 S
T 28 S
T 29 S
T 30 S
T 14 S
T 15 S
T 16 S
T 17 S
T 18 S
T 19 S
T 20 S
T 21 S
R 28 E
R 29 E
R 31 E
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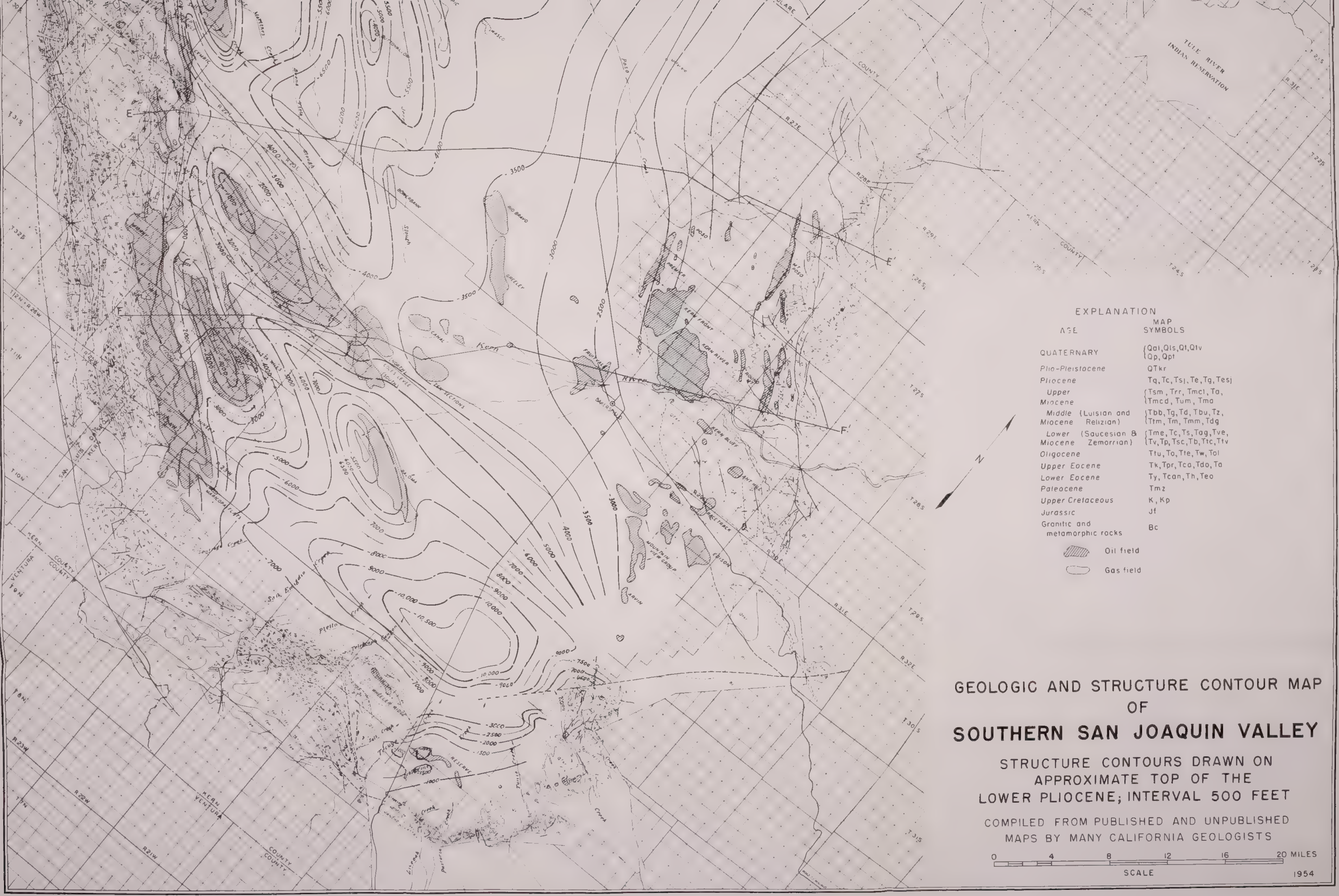
3000
2500
2000
1500
1000
500



EXPLANATION

AGE	MAP SYMBOLS
QUATERNARY	Qal, Qls, Ql, Qlv Qp, Qpt
Plio-Pleistocene	QTkr
Pliocene	Tq, Tc, Tsj, Te, Tg, Tesj
Upper Miocene	Tsm, Trr, Tmcl, Ta, Tmcd, Tum, Tma
Middle Miocene (Luisian and Relizian)	Tbb, Tg, Td, Tbu, Tz, Ttm, Tm, Tmm, Tdg
Lower Miocene (Saucesian & Zemorrian)	Tme, Tc, Ts, Tag, Tve, Tv, Tp, Tsc, Tb, Ttc, Ttv
Oligocene	Ttu, To, Tte, Tw, Tol
Upper Eocene	Tk, Tpr, Tca, Tdo, Ta
Lower Eocene	Ty, Tcan, Th, Teo
Paleocene	Tmz
Upper Cretaceous	K, Kp
Jurassic	Jf
Granitic and metamorphic rocks	Bc
▨	Oil field
⬭	Gas field

GEOLOGIC AND STRUCTURE CONTOUR MAP OF SOUTHERN SAN JOAQUIN VALLEY

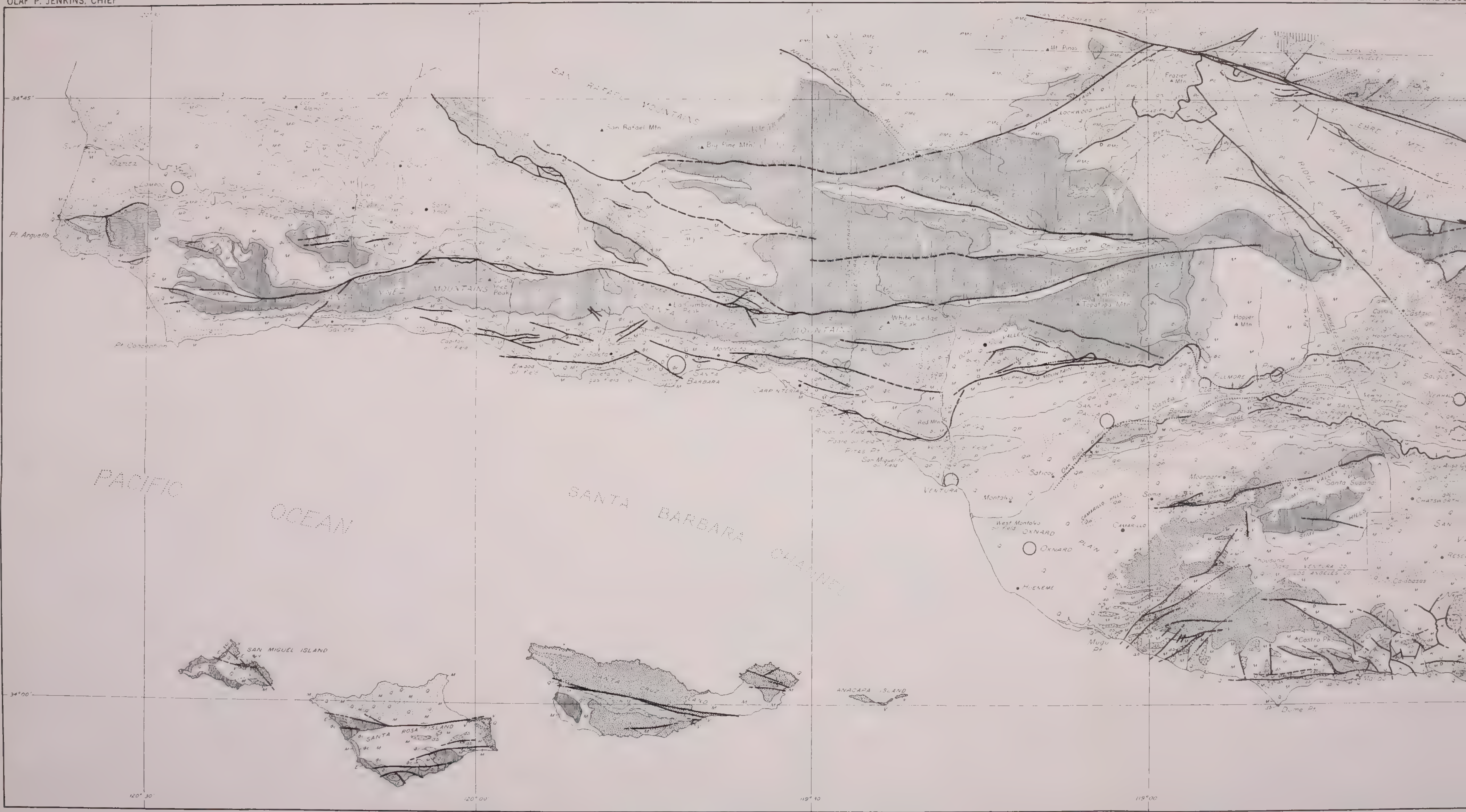
STRUCTURE CONTOURS DRAWN ON
APPROXIMATE TOP OF THE
LOWER PLIOCENE; INTERVAL 500 FEET

COMPILED FROM PUBLISHED AND UNPUBLISHED
MAPS BY MANY CALIFORNIA GEOLOGISTS

0 4 8 12 16 20 MILES

SCALE

1954



GEOLOGIC MAP OF TRANSVERSE RANGE P

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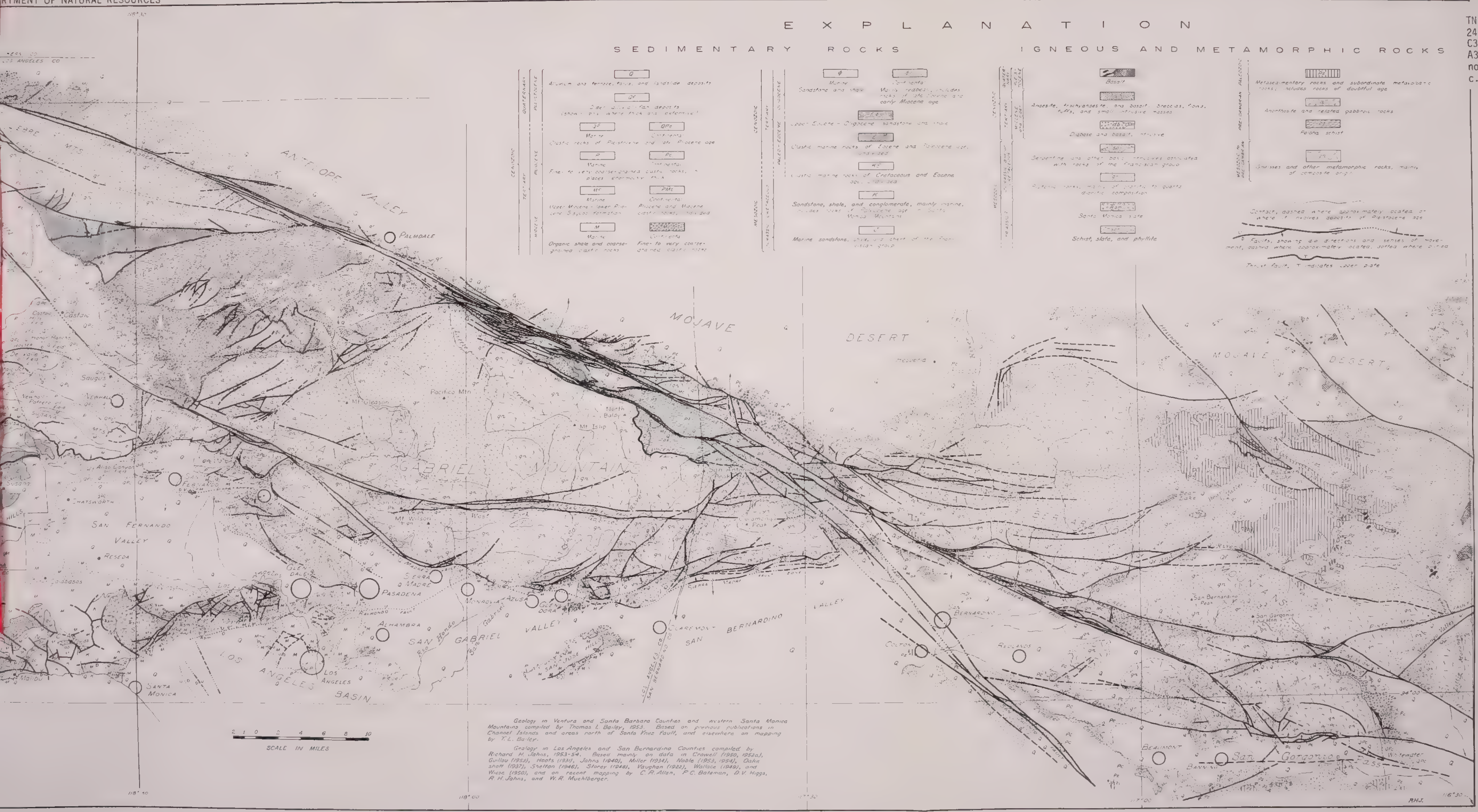
EXPLANATION
SEDIMENTARY ROCKS
Q
Alluvium and terrace, talus, and landslide deposits
Qf
Older alluvial fan deposits (shown only where thick and extensive)
QP
Marine
QPc
Continental
Clastic rocks of Pleistocene and late Pliocene age
P
Marine
Pc
Continental
Fine- to very coarse-grained clastic rocks, in places enormously thick
MP
Marine
Upper Miocene - lower Pliocene Saugus formation
PMc
Continental
Pliocene and Miocene clastic rocks, undivided
M
Marine
Organic shale and coarse-grained clastic rocks
Mc
Continental
Fine- to very coarse-grained clastic rocks
Φ
Marine
Sandstone and shale
Φc
Continental
Mainly redbeds; includes rocks of late Eocene and early Miocene age
EΦ
Upper Eocene - Oligocene sandstone and shale
E
Clastic marine rocks of Eocene and Paleocene age, undivided
KE
Clastic marine rocks of Cretaceous and Eocene age, undivided
K
Sandstone, shale, and conglomerate, mainly marine; includes rocks of Paleocene age in Santa Monica Mountains
Jf
Marine sandstone, shale, and chert of the Franciscan group
QUATERNARY
PLEISTOCENE
TERTIARY
PLIOCENE
MIOCENE
CENOZOIC
OLIGOCENE
PALEO-EOCENE
MESOZOIC
CRETACEOUS
JURASSIC
IGNEOUS AND METAMORPHIC ROCKS
Basalt
Andesite, trachyandesite, and basalt breccias, flows, tuffs, and small intrusive masses
db
Diabase and basalt, intrusive
sp
Serpentine and other basic intrusives associated with rocks of the Franciscan group
gr
Plutonic rocks, mainly of granitic to quartz dioritic composition
Rsm
Santa Monica slate
sch
Schist, slate, and phyllite
Pz
Metasedimentary rocks and subordinate metavolcanic rocks; includes rocks of doubtful age
a
Anorthosite and related gabbroic rocks
ps
Pelona schist
gn
Gneisses and other metamorphic rocks, mainly of composite origin
PALEOZOIC
PRE-CAMBRIAN
MESOZOIC & PRE-CAMBRIAN
TRIASSIC
Contact, dashed where approximately located or where it involves deposits of Pleistocene age
U
D
Faults, showing dip directions and senses of movement, dashed where approximately located, dotted where buried
T
Thrust fault, T indicates upper plate
LOS ANGELES CO
SIERRA MTS
SAN ANDREAS FAULT
ANTELOPE VALLEY
PALMDALE
MOJAVE
DESERT
MOJAVE DESERT
Castaic
Saugus
Newhall
Mt Gleason
Pacific Mtn
North Baldy
Mt Islip
SAN GABRIEL MOUNTAINS
SAN GABRIEL FAULT
Mt Wilson
San Fernando
Chatsworth
SAN FERNANDO VALLEY
Reseda
Calabasas
Glendale
Pasadena
Sierra Madre
Monrovia
Azusa
Glendora
Alhambra
RAYMOND FAULT
SAN GABRIEL VALLEY
Rio Hondo
San Gabriel River
SAN JOSE HILLS
LOS ANGELES BASIN
Los Angeles
Santa Monica
Malibu
Claremont
SAN BERNARDINO VALLEY
LOS ANGELES CO
SAN BERNARDINO CO
San Bernardino
Colton
Redlands
SAN BERNARDINO MOUNTAINS
San Bernardino Peak
San Gorgonio Mtn
Big Bear Lake
Beaumont
Banning
San Gorgonio Pass
Whitewater
Hesperia
Palm Springs
2 1 0 2 4 6 8 10
SCALE IN MILES
118°30
118°00
117°30
117°00
116°30
34°00
RHJ.

Geology in Ventura and Santa Barbara Counties and western Santa Monica Mountains compiled by Thomas L. Bailey, 1953. Based on previous publications in Channel Islands and areas north of Santa Ynez fault, and elsewhere on mapping by T. L. Bailey.

Geology in Los Angeles and San Bernardino Counties compiled by Richard H. Jahns, 1953-54. Based mainly on data in Crowell (1950, 1952a), Guillou (1953), Hoots (1931), Jahns (1940), Miller (1934), Noble (1953, 1954), Oakeshott (1937), Shelton (1946), Storey (1948), Vaughan (1922), Wallace (1949), and Wiese (1950), and on recent mapping by C. R. Allen, P. C. Bateman, D. V. Higgs, R. H. Jahns, and W. R. Muehlberger.

SE RANGE PROVINCE, SOUTHERN CALIFORNIA

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TN
24
C3
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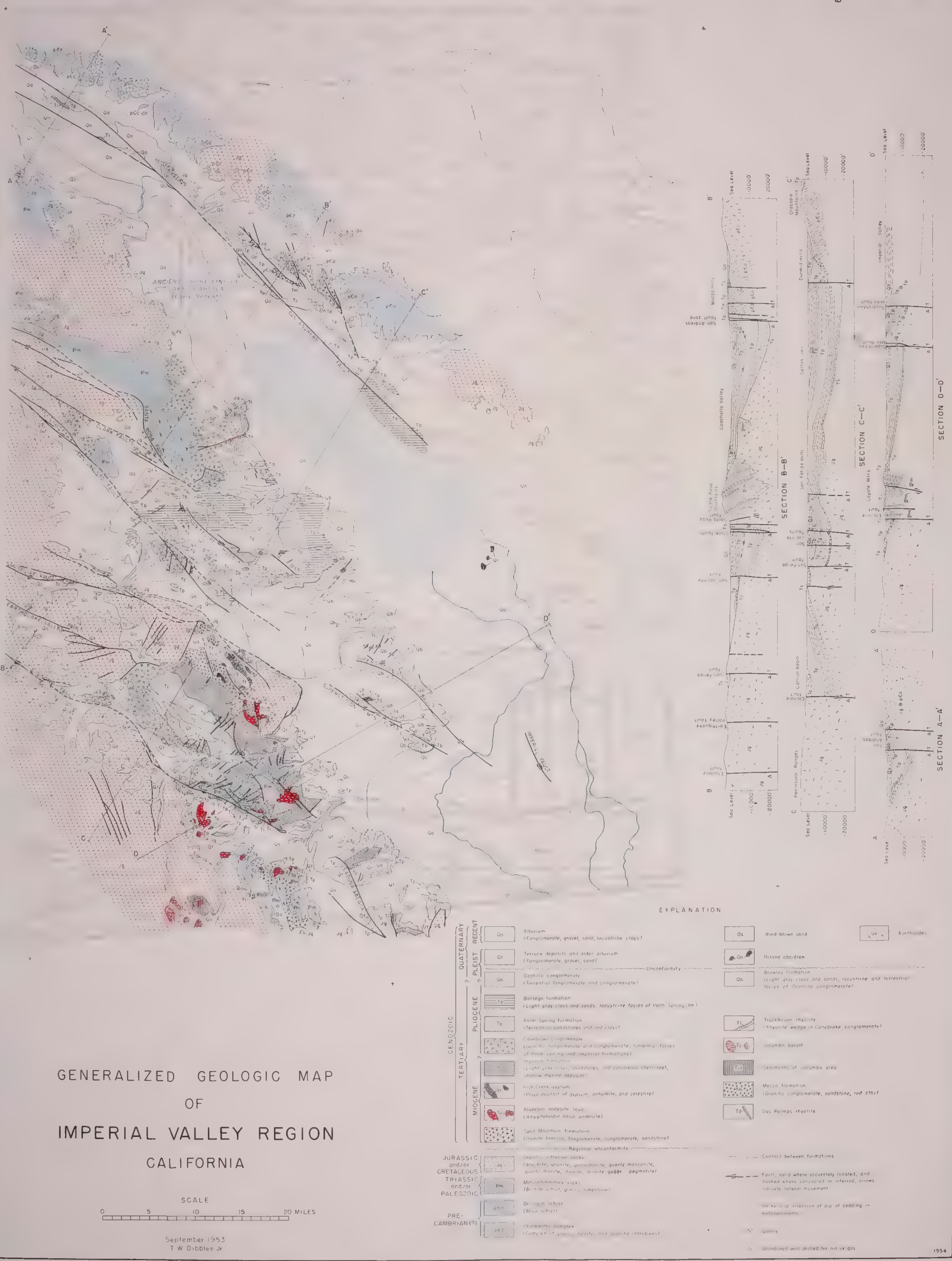
BULL 170 CHAPT II
CONT 2 PLATE 2


A
A'
B
B'
C
C'
D
D'
SAN ANDREAS FAULT
SANTA ROSA FAULT
CLARK FAULTS
SAN JACINTO FAULT
EARTHQUAKE VALLEY FAULT
SUPERSTITION HILLS FAULT
IMPERIAL FAULT
LAGUNA SALADA FAULT
ANCIENT SHORE LINE OF LAKE CAHUILLA (Early Recent)
Qa
Qt
Qo
Qb
Qs
Qn
Tb
Tp
Tc
Ti
Tm
Td
Jg
Pm
pCo
pCc
SECTION A—A'
SECTION B—B'
SECTION C—C'
SECTION D—D'
Sea Level
-10000'
-20000'
Mecca Hills
San Andreas fault zone
Coachella Valley
Santa Rosa Mountains
Clark faults
San Jacinto fault
San Felipe fault
Earthquake Valley fault
Elsinore fault
Orocopia Mountains
Durmid Hills
Salton sea
San Felipe Hills
Coyote Mtns
Imperial Valley
Superstition Mtn fault
Superstition Hills fault
Carrizo basin
Peninsular Ranges
EXPLANATION
CENOZOIC
QUATERNARY
TERTIARY
RECENT
PLEIST
PLIOCENE
MIOCENE
Qa Alluvium (Fanglomerate, gravel, sand, lacustrine clays)
Qt Terrace deposits and older alluvium (Fanglomerate, gravel, sand)
Unconformity
Qo Ocotillo conglomerate (Torrential fanglomerate and conglomerate)
Tb Borrego formation (Light gray clays and sands, lacustrine facies of Palm Spring fm.)
Tp Palm Spring formation (Terrestrial sandstones and red clays)
Tc Canebrake conglomerate (Granitic fanglomerate and conglomerate, torrential facies of Palm Spring and Imperial formations)
Imperial formation (Light gray clays, sandstones, and calcareous shell-reef, shallow marine deposits)
Tf Fish Creek gypsum (Playa deposit of gypsum, anhydrite, and celestite)
Ta Alverson andesite lava (Amygdaloidal basic andesite)
Ts Split Mountain formation (Diorite breccia, fanglomerate, conglomerate, sandstone)
Regional unconformity
JURASSIC and/or CRETACEOUS
Jg Granitic intrusive rocks (Alaskite, granite, granodiorite, quartz monzonite, quartz diorite, diorite, diorite-gabbro, pegmatite)
TRIASSIC and/or PALEOZOIC
Pm Metasedimentary rocks (Biotite schist, gneiss, limestone)
PRE-CAMBRIAN(?)
pCo Orocopia schist (Mica schist)
pCc Chuckwalla complex (Complex of gneiss, diorite, and granitic intrusives)
Qs Wind-blown sand
Qe Earthslides
Qn Niland obsidian
Qb Brawley formation (Light gray clays and sands, lacustrine and terrestrial facies of Ocotillo conglomerate)
Tt Truckhaven rhyolite (Rhyolite wedge in Canebrake conglomerate)
Tj Jacumba basalt
Tjs Sediments of Jacumba area
Tm Mecca formation (Granitic conglomerate, sandstone, red clay)
Td Dos Palmas rhyolite
Contact between formations
Fault, solid where accurately located, and dashed where concealed or inferred; arrows indicate lateral movement
Strike and direction of dip of bedding in metasediments
Quarry
Abandoned well drilled for oil or gas

GENERALIZED GEOLOGIC MAP
OF
IMPERIAL VALLEY REGION
CALIFORNIA

SCALE
0 5 10 15 20 MILES

September 1953
T W Dibblee Jr

1954

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UNITED STATES DEPARTMENT OF THE INTERIOR
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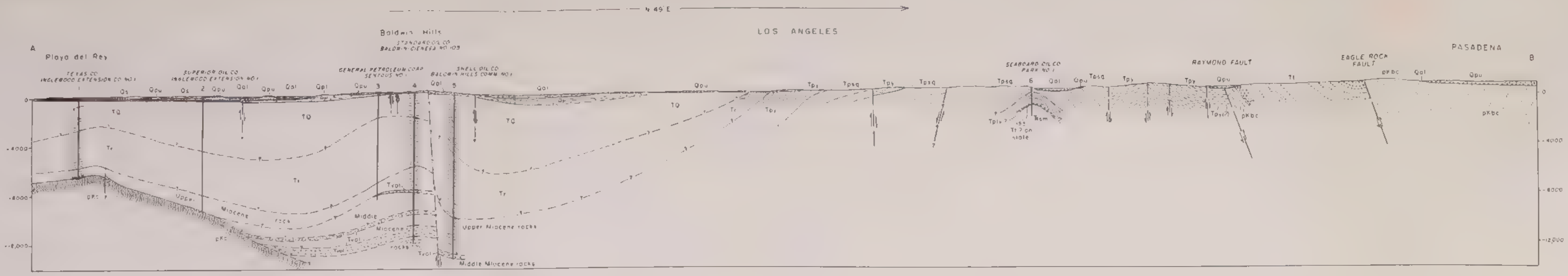
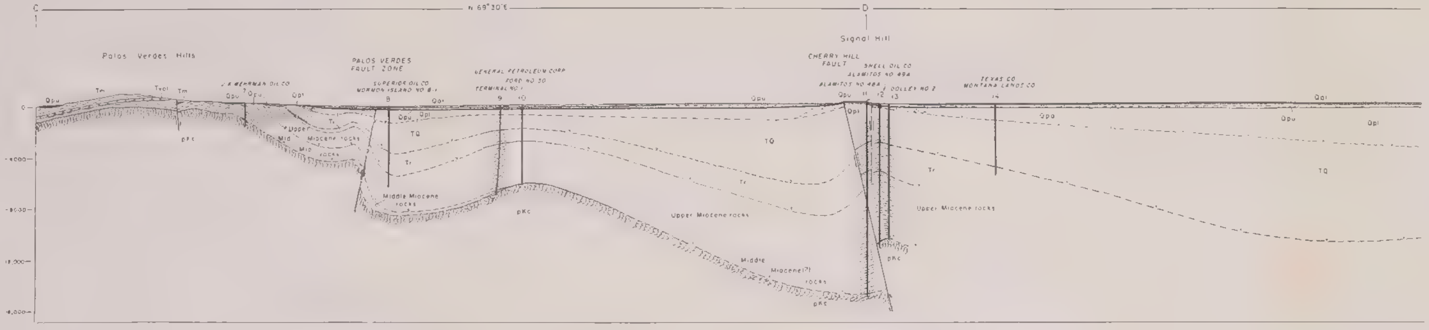
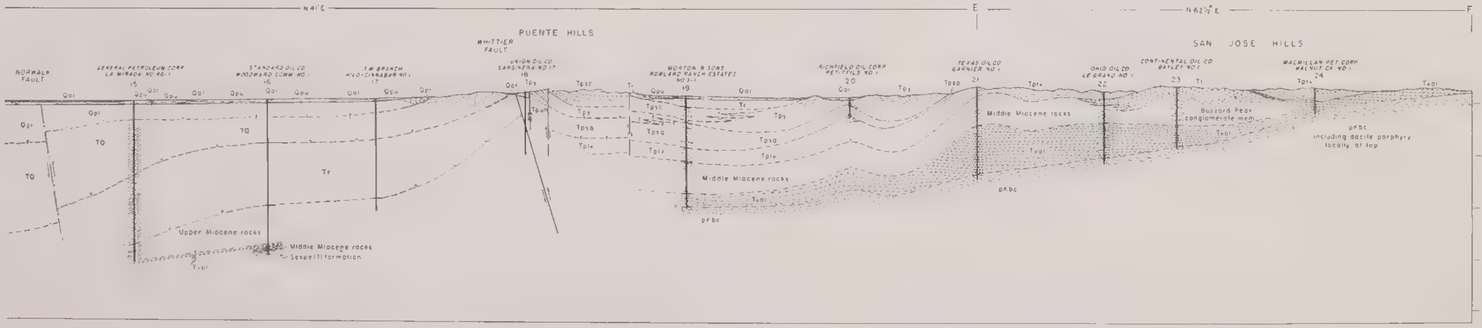
BULL 170 CHAPT II
CONT 5 PLATE 1A



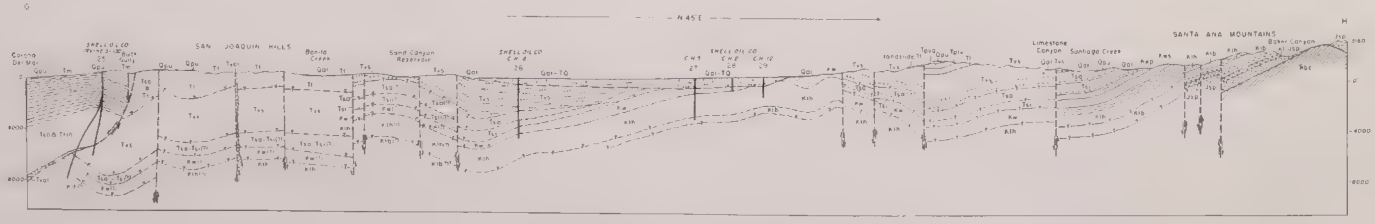
STRUCTURE SECTION A-B, PLAYA DEL REY TO PASADENA



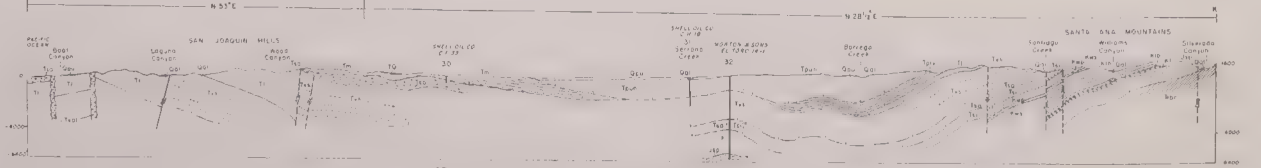
SOUTHWESTERN PART OF SECTION C-D-E-F, PALOS VERDES HILLS TO MOUNTAIN MEADOWS



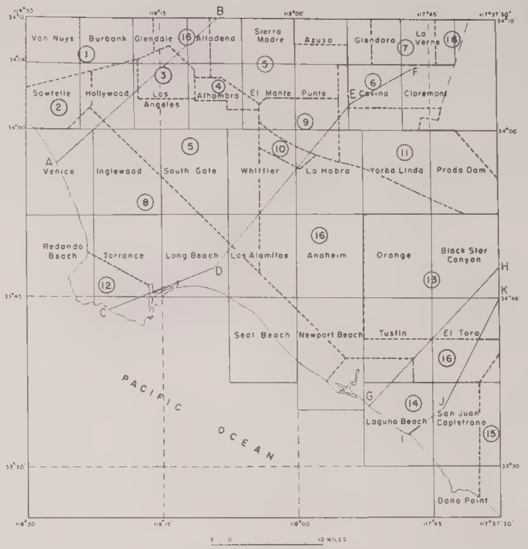
NORTHEASTERN PART OF SECTION C-D-E-F, PALOS VERDES HILLS TO MOUNTAIN MEADOWS



STRUCTURE SECTION G-H, CORONA DEL MAR TO BAKER CANYON



STRUCTURE SECTION I-J-K, LAGUNA BEACH TO SILVERADO CANYON



INDEX MAP SHOWING LINES OF STRUCTURE SECTIONS, QUADRANGLES AND SOURCES OF GEOLOGY

1 Cordell Durrell, this volume *
2 U.S. Geol Survey Prof Paper 165-C (1931) *
3 Unpublished map of P H Dudley, Richfield Oil Corp *
4 Unpublished map of Miller Quarles, Jr, California Institute of Technology *
5 Rollins Eckis, California Div of Water Resources (1934)
6 Unpublished map by J S Shelton, Pomona College
7 U.S Geol Survey Oil and Gas Inv Prelim Map 63 (1946)
8 Unpublished maps by J. F Poland et al, U.S. Geol Survey Ground Water Branch (1945, 1947) *
9 U.S Geol Survey Oil and Gas Inv Prelim Map 83 (1949) and H E. Stark, Am Assoc. Petroleum Geologists Bull (in press) *
10 C J Kundert, California Div of Mines (1952) *
11 U.S. Geol. Survey Oil and Gas Inv Prelim Map 23 (1944) *
12 U S Geol Survey Prof Paper 207 (1946)
13 U S Geol Survey Oil and Gas Inv Map OM 154 (in press)
14 Unpublished maps by P H Dudley, R. E. Pearson, and J.G Elam of Richfield Oil Corp and by G L. Dalton and G H Clark of Claremont Graduate School *
15 A O Woodford, Univ. of Calif Pub (1925) and unpublished map by W S T. Smith and R R Morse *
16 U S Geol Survey reconnaissance mapping for this publication

* *Modified by the compilers*

EXPLANATION

Recent	Qal	Alluvium	
	Qs	Sand Dunes	
Upper Pleistocene	Qpu	Terrace deposits	
Lower Pleistocene	Qpl	San Pedro sand, Timms Pt silt Lomita marl, La Habra conglomerate	
Lower Pleistocene Upper Pliocene	TQ	San Mateo fm, Pico fm, Repetto fm and Duarte conglomerate	
Upper Pliocene	Tpu	Upper Pliocene rocks	
Lower Pliocene	Tr	Repetto formation	
Upper Miocene	Tpsc	Sycamore Canyon member	Puente fm
	Tpy	Yorba member	
	Tpsq	Soquel member	
	Tplv	La Vida member	
Middle & Upper Miocene	Tm	Monterey shale	
Middle Miocene	Tso	San Onofre breccia	
	Tt	Topanga formation	
Lower Miocene to Upper Eocene	Tvs	Vaqueros and Sespe fm undiff	
Middle Eocene	Tsa	Santiago formation	
Paleocene	Tsi	Silverado and Martinez fm	
Upper Cretaceous	Kwp	Pleasants sandstone member	Williams fm
	Kws	Schulz Ranch sandstone member	
	Klh	Holz shale member	Ladd fm
	Klb	Baker Canyon member	
	Kt	Trabuco formation	
Middle Miocene	Tvol	Tertiary volcanic rocks	
Jurassic (?)	Jsp	Santiago Peak volcanic rocks	
Triassic	℞bc	Bedford Canyon formation	
Mesozoic	pKbc	Basement complex	

STRUCTURE SECTIONS ACROSS THE LOS ANGELES BASIN AREA

By
J E Schoellhamer, R F Yerkes and J G Vedder
U S Geological Survey

1 0 1 2 3 MILES

Accompanying Bull 170, Chapt II, Cont 5, Geology of the Los Angeles Basin, by A O Woodford, J E Schoellhamer, J G Vedder and R F Yerkes

1954

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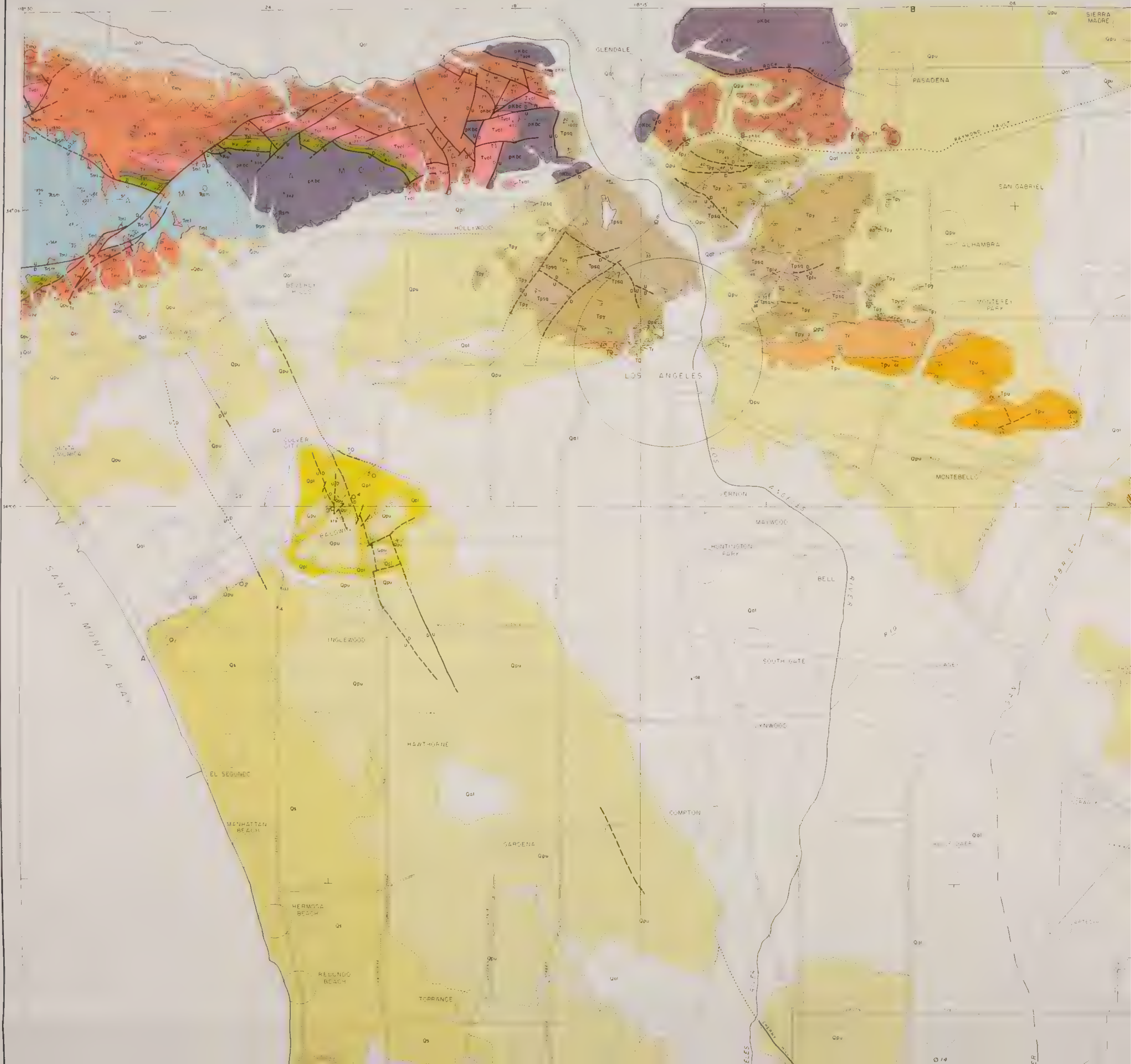

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BULL 170, CHAP II
CONT 5 PLATE I

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no.1
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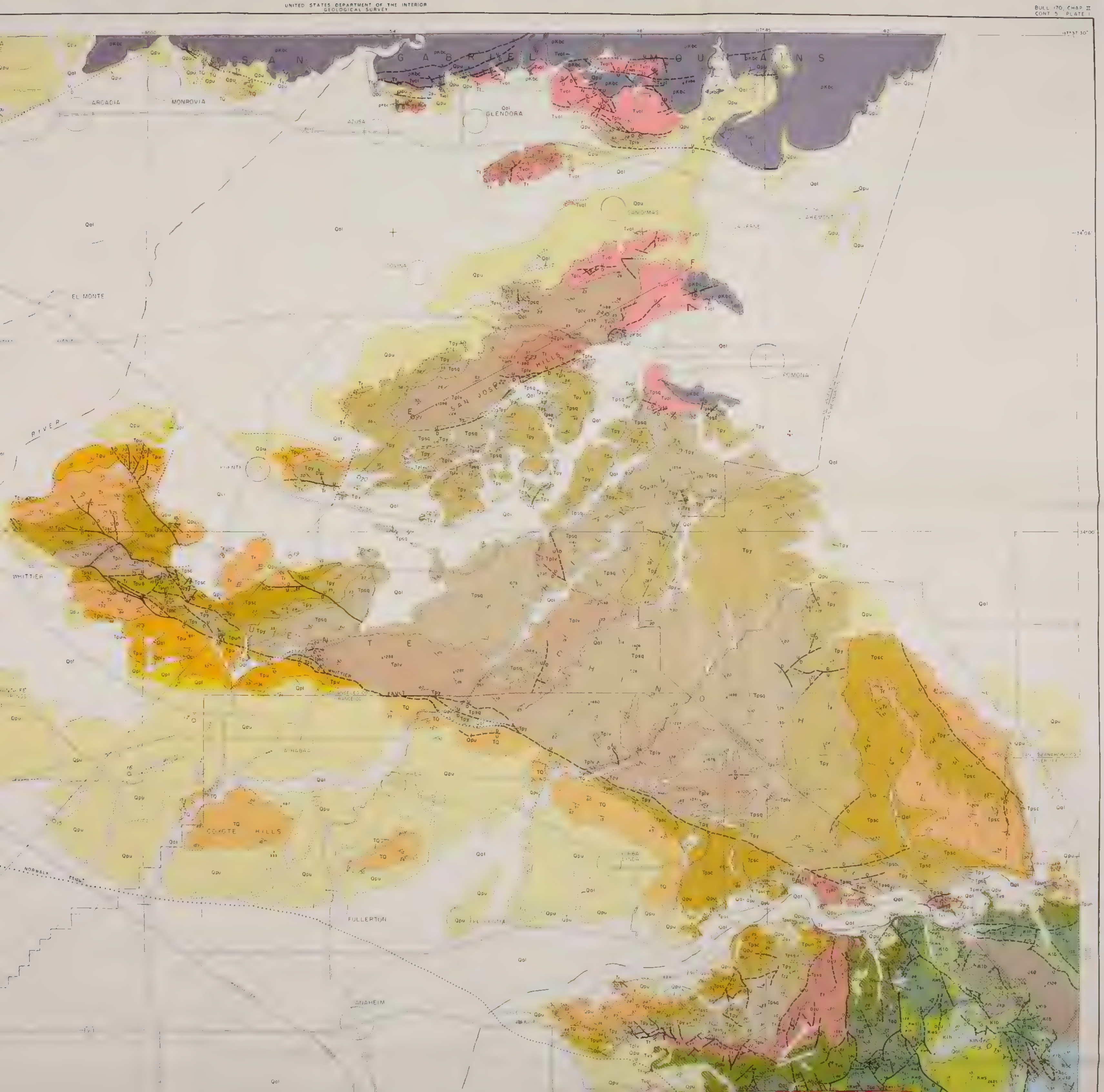

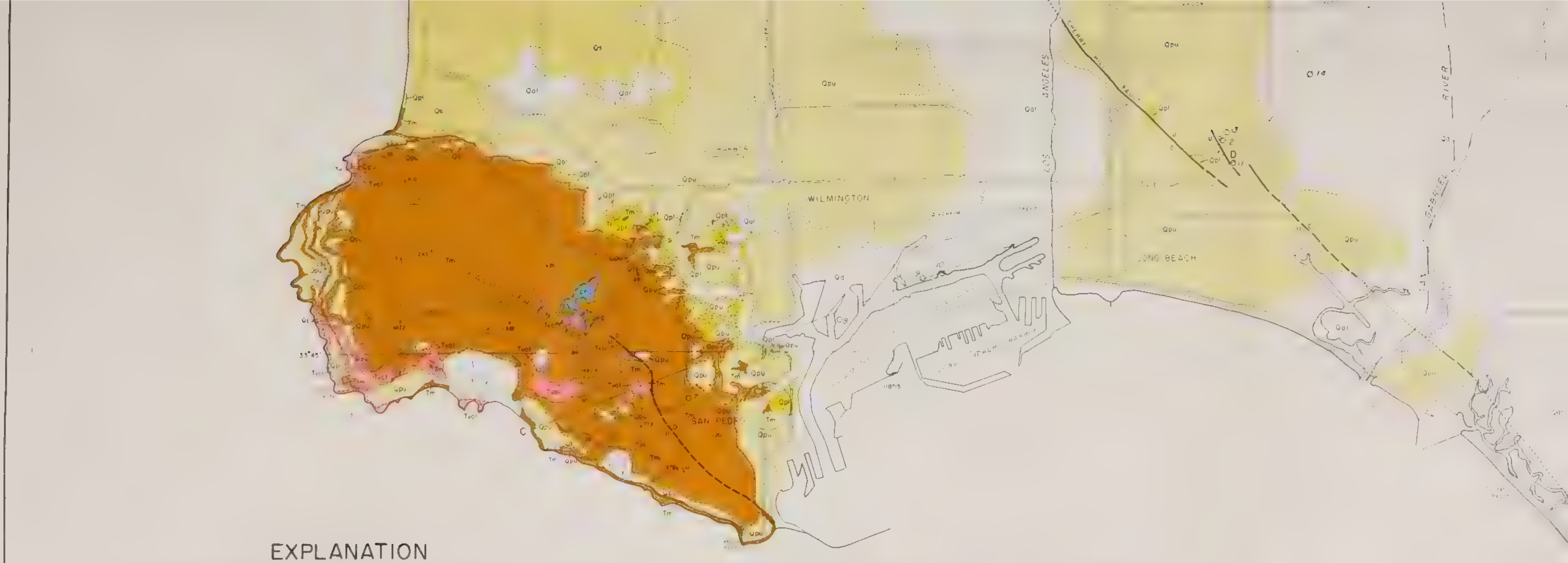

EXPLANATION

QUATERNARY AND TERTIARY SEDIMENTARY ROCKS

	Palos Verdes Hills area	Santa Monica Mountains west of Cahuenga Pass	San Joaquin Hills area	Puente Hills, Santa Ana Mountains area	Los Angeles city, Montebello area	
Recent	Qal Alluvium	Qal Alluvium	Qal Alluvium	Qal Alluvium	Qal Alluvium	QUATERNARY
	Qs Sand dunes (Torrance-Redondo area)					
Pleistocene: Upper Pleistocene	Qpu Terrace deposits and Palos Verdes sand	Qpu Terrace deposits and Palos Verdes sand	Qpu Terrace deposits and Palos Verdes sand	Qpu Terrace deposits and Palos Verdes sand	Qpu Terrace deposits and Palos Verdes sand	
Pleistocene: Lower Pleistocene	Qpl San Pedro sand, Timms Point silt, Lomita marl	Qpl San Pedro sand, Timms Point silt, and Lomita marl (Baldwin Hills area)		Qpl La Habra conglomerate of Eckis (1934) (south side of Puente Hills)		
Pliocene: Upper Pliocene			TQ San Mateo formation and rocks commonly called Pico formation (near Newport Beach)	TQ Rocks commonly called Pico fm, Duarte conglomerate (north of Puente Hills), some upper Pliocene rocks and rocks commonly called Repetto fm (south of Whittier fault)	TQ Rocks commonly called Pico fm	TERTIARY
				Tpu Upper Pliocene rocks	Tpu Upper Pliocene rocks	
Pliocene: Lower Pliocene	Tr Rocks commonly called Repetto formation		Tr Rocks commonly called Repetto formation near Newport Beach	Tr Rocks commonly called Repetto formation	Tr Rocks commonly called Repetto formation	
Miocene: Upper Miocene			Tc Capistrano formation			
		Tmu / Tml Modelo formation (Tmu-upper member, Tml lower member)		Tpun / Tpsc / Tpy / Tpsq / Tplv Puente formation (Tpun-Puente fm undivided, Tpsc-Sycomore Canyon member, Tpy-Yorba member, Tpsq-Soquel member, Tplv-La Vida member)	Tpy / Tpsq / Tplv Puente formation (Tpy-Yorba member, Tpsq-Soquel member, Tplv-La Vida member)	
Middle and upper Miocene	Tm Monterey shale		Tm Monterey shale			
Middle Miocene			Tso San Onofre breccia			
		Tt Topanga formation	Tt Topanga formation	Tt Topanga formation	Tt Topanga formation	
Lower Miocene, Oligocene, Upper Eocene			Tsv Vaqueros and Sespe formations undifferentiated	Tsv Vaqueros and Sespe formations undifferentiated		
Eocene: Middle Eocene				Tsa Santiago formation		
Paleocene		Tma Martinez formation		Tsi Silverado formation		

CRETACEOUS SEDIMENTARY ROCKS

	Palos Verdes Hills area	Santa Monica Mountains west of Cahuenga Pass	San Joaquin Hills area	Puente Hills, Santa Ana Mountains area	
Upper Cretaceous		Ku Undifferentiated upper Cretaceous rocks assigned to Chico fm by Hoots		Kw / Kwp / Kws Williams formation (Kw-Williams fm undivided, Kwp-Pleasants sandstone member, Kws-Schulz Ranch sandstone member)	CRETACEOUS
				Klh / Klb Ladd formation (Klh-Holz shale member, Klb-Baker Canyon conglomerate member)	
				Kt Trabuco formation	

VOLCANIC ROCKS

Miocene: Middle Miocene	Tvol Basalt interbedded with Monterey shale	Tvol Basalt, intrusive and extrusive	Tvol Andesite and basalt, intrusive and extrusive	Tvol Glendora volcanics, El Modeno volcanics, etc	TERTIARY

METAMORPHIC ROCKS

Western bedrock complex

- pKc [illegible] schist (Mesozoic or older) — MESOZOIC(?)
- Ŧsm Santa Monica slate — TRIASSIC(?)

Eastern bedrock complex

- Jsp Santiago Peak volcanics (Santa Ana Mountains) — JURASSIC
- Ŧbc Bedford Canyon formation (Santa Ana Mountains) — TRIASSIC

PLUTONIC ROCKS

- pKbc Granite (intrudes Santa Monica slate) — JURASSIC (?)
- pKbc Basement rocks of San Gabriel Mts and adjoining areas — MESOZOIC

MAP SYMBOLS

Contact (dashed where approximately located)

Fault (dashed where approximately located) (U: upthrown side, D: downthrown side)

Concealed fault

Strike and dip of beds

Strike and dip of overturned beds

Horizontal beds

Landslide (arrows indicate direction of movement)

○ Holes drilled for oil

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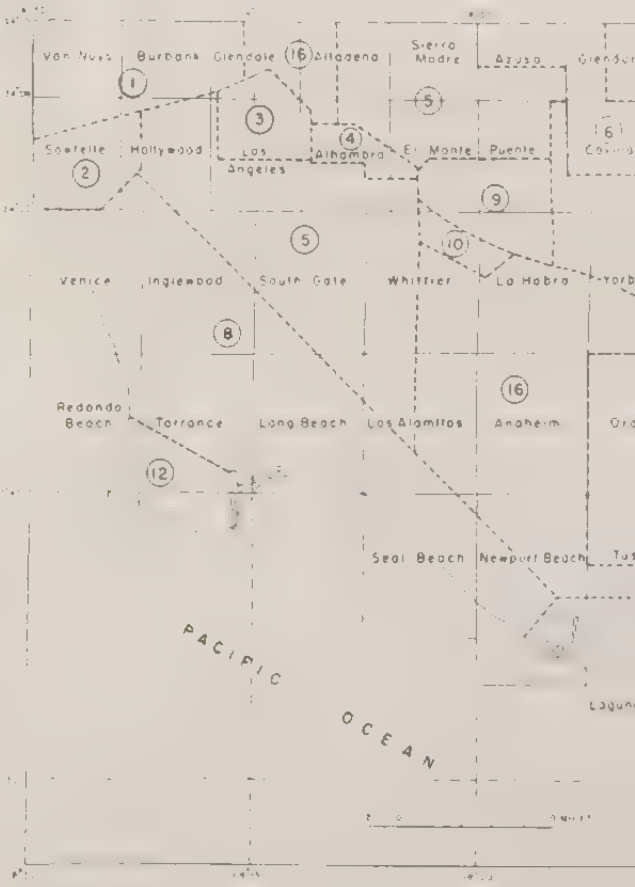

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2 U S Geol Survey Prof Paper 165-C (1931)*
3 Unpublished map by P H Dudley, Richfield Oil Corp*
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GEOLOGY OF THE LOS ANGE

Compiled by J E Schoellhamer, J G Vedder, and
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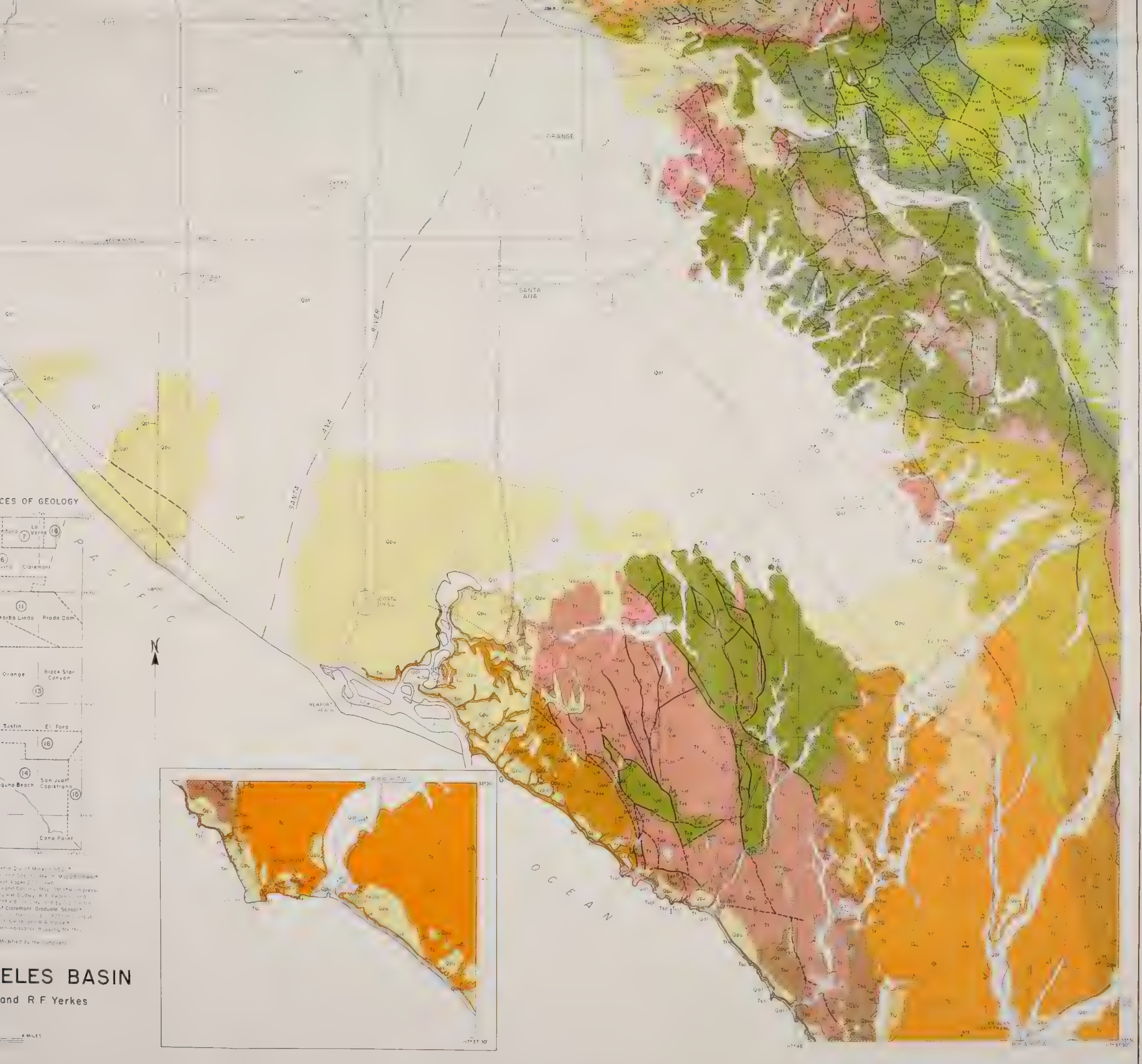

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and R.F. Yerkes

Accompanying Bull 170, Chap II, Cont 5, Geology of the Los Angeles Basin,
by A O Woodford, J E Schoellhamer, J G Vedder, and R F Yerkes

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DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER VI
HYDROLOGY

1954

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San Francisco
Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER VI

HYDROLOGY

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Editorial Note:

CHAPTER SIX is a brief treatment of a very broad subject—the occurrence and behavior of surface water and ground-water in southern California. The movements of incoming air masses, together with the marked topographic irregularities in the region, are responsible for a pattern of precipitation that appears to be broadly systematic in both space and time. In detail, however, this pattern is highly variable. Most of the precipitation is consumed by native vegetation or is lost to the atmosphere by evaporation from plants or the ground surface, and much of the remainder penetrates beneath the surface and is circulated as ground-water. Ordinarily only a little water appears as surface run-off, and, except during infrequent severe floods, only a small part of this flow reaches the ocean or debouches onto playa lakes in the desert basins of the interior.

The moisture budget is fundamental to problems of water use and flood control in both the coastal and interior portions of southern California, and it is of particular significance in the Los Angeles region, which contains nearly half of the people in the State but receives only about one percent of the State's annual precipitation. Also of great significance are the corollary problems of occurrence and nature of ground-water, which in turn involve the rocks, surficial materials, and fault and fracture zones through which it moves. Detailed geologic studies are being focused increasingly upon the many basins in which lowered ground-water tables suggest that withdrawals have seriously exceeded natural recharge, or in which some of the waters have been contaminated by salt water or industrial wastes. Although it has been necessary to bring water into the coastal portion of southern California from other regions since 1913, the local sources of supply continue to be of profound importance.

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1. HYDROLOGY OF THE LOS ANGELES REGION[*]

By Harold C. Troxell † and Walter Hofmann †

The Los Angeles region includes the major drainage areas of the Santa Ana, San Gabriel, and Los Angeles Rivers, together with the coastal plain from Newport Beach to Malibu Beach. The 1950 census indicates that 4,760,000 people, or about 45 percent of the State's entire population, reside in this relatively small area. The estimated annual water requirements of this region have increased from about 200,000 acre-feet in 1900 to 1,400,000 acre-feet in 1950.

CLIMATE

Historically the climate of the coastal plain and valleys of the Los Angeles region has been classified as Mediterranean because of the mild winters of limited precipitation and the warm dry summers. Thornthwaite (1931) has proposed an empirical equation that gives a more exacting climatic classification based on the relationship between precipitation and evaporation. On this basis, the general climatic distribution from the ocean across the plains and mountains to the desert beyond, along a typical profile from Long Beach through San Bernardino to Barstow, is shown in figure 1. The climate ranges from humid to arid within a distance of less than 80 miles along this profile. Few places in the United States have so wide a climatic range in such relatively small distances.

Owing to the modifying influences of the ocean breezes, the monthly temperatures in the semiarid regions of the coastal plain pass through the relatively small range of only 18 degrees at Long Beach. With the exception of the two summer months of July and August, the monthly air temperatures remain continuously in the warm classification of 50° to 68° F. (Jefferson, 1938; Hartshorne, 1938.)

In contrast, farther inland in the semiarid regions of the upper Santa Ana Valley, the range in monthly temperature increases to 28 degrees at San Bernardino, with eight of the months being classed as warm and four as hot. Still farther inland, in the humid part of the San Bernardino Mountains, all the temperatures show a decline due to altitude, but retain about the same range in monthly values.

In the arid Mojave Desert, north of the San Bernardino Mountains and still farther from the ocean, the monthly temperatures at Barstow show a range of 38 degrees, with four of the months being classified as hot, two as cool, and the remainder as warm.

The eastward or northeastward moving masses of moisture-laden Pacific air, in passing through the Los Angeles region, are retarded and elevated by the first mountain barrier, the Santa Ana Mountains. Condensation occurs as a result. The average annual precipitation is about 13 inches at the coastal city of Long Beach, and most of this falls during the mild winter months of December through March. About 96 percent of the annual precipitation generally occurs in the 7-month period of October through April, leaving only 4 percent for the summer dry period.

As the moisture-laden air masses move farther inland, they are further elevated by the somewhat higher divide of the San Bernardino Mountains. The effect of this elevating is reflected in the gradually increasing precipitation from Corona to San Bernardino. Owing to these orographic conditions, the annual precipitation increases beyond San Bernardino to more than 40 inches at Squirrel Inn near the divide. This greater precipitation is largely responsible for the humid climatic classification shown in figure 1.

Across the divide, the warming of the air masses in the arid Mojave Desert causes the annual precipitation to decrease rapidly to 4.5 inches at Barstow. Under these desert conditions, the summer convectional storms or thunderstorms produce a larger portion of the annual precipitation. The precipitation at Barstow for the months of May through September is 46 percent greater than that observed at Long Beach for the same period.

PRECIPITATION

As in most arid and semiarid regions, the annual precipitation in the Los Angeles region is extremely variable. This variability is shown by the observed precipitation at Los Angeles, which ranges from as little as 5.59 inches in the climatological year ending on June 30, 1899, to 38.18 inches in the climatological year ending on June 30, 1884, with an average for a 75-year period of 15.22 inches. This wide variability in precipitation is greatly accentuated by recurring sequences of years in which the dry or the wet years tend to predominate, as shown in figure 2.

The upper part of figure 2 gives the observed annual precipitation at Los Angeles for the entire 75-year period from July 1, 1877, to June 30, 1952. In the lower part, the cumulative departures from the 75-year average value are shown for each year since the beginning of the record in 1877. In this type of diagram, an upward trend represents a sequence of years in which the wet years predominate, whereas a downward trend indicates that the dry years predominate. By this means it has been possible to divide the annual

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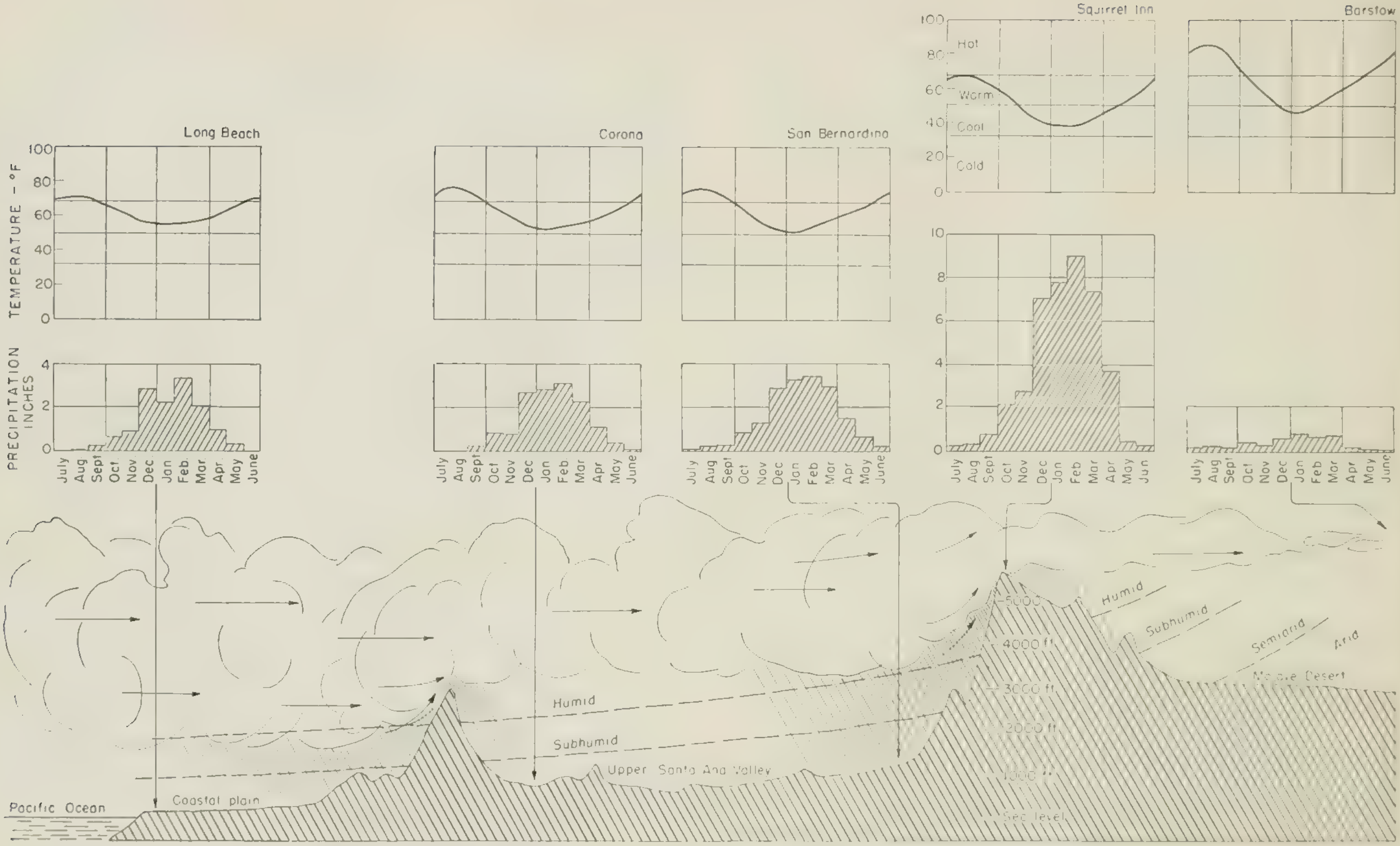

Figure 1. Climatic distribution, including temperature and precipitation, from the ocean to the desert.

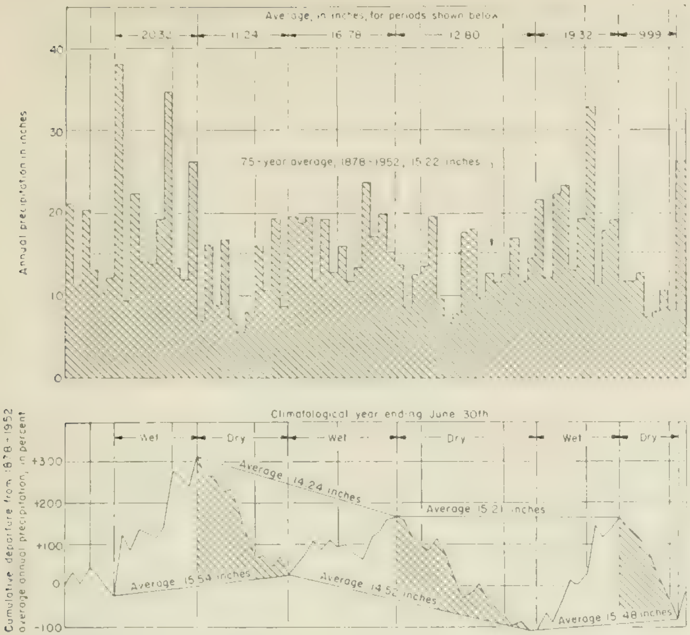

FIGURE 2. Annual precipitation at Los Angeles, California, for the period 1878 to 1952.

precipitation record into wet and dry periods. The average annual precipitation for each of these sequences is given across the upper part of figure 2. These averages range from 9.99 inches for the 7-year sequence of 1945-51 to 20.32 inches for the 10-year sequence of 1884-93.

In order to eliminate the possibility of bias, it is necessary that the basic analytical periods include equal numbers of wet and dry sequences. The simplest or primary base periods are those containing a single wet and a single dry sequence. The average annual precipitation, as well as the beginning and ending of each of these primary base periods, are indicated in the lower part of figure 2. The longest available basic analytical period at this station would be the 68-year period of 1883 to 1951, which contains 3 wet and 3 dry sequences, and has an average value of 15.08 inches for annual precipitation.

Recurring Wet and Dry Periods. In semiarid and arid areas such as the Los Angeles region the general public always is extremely conscious of these wet and dry sequences. In fact, one of the most common questions asked of the hydrologist is, "How long do these wet and dry periods last?" Probably the best answer to this question was given by Schulman (1947), who found that by a careful selection of Bigcone spruce in the San Bernardino, San Jacinto, San Gabriel, and Palomar Mountains, a fairly reliable record of wet and dry years could be obtained by measuring the widths of the annual tree-rings. By means of these data, he was able to develop a continuous record that tended to reflect the annual precipitation for the 560-year period from 1385 to 1944. This record, starting about 157 years before Cabrillo first sailed along the California coast and 235 years before the Pilgrims landed at Plymouth, is given in figure 3.

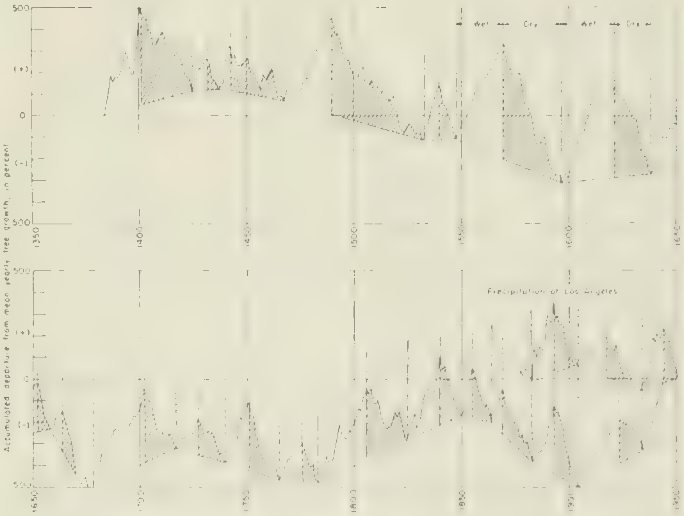

FIGURE 3. Wet and dry periods as indicated by the annual tree-ring growth of Bigcone spruce in southern California.

The succession of wet and dry years is shown by plotting the cumulative departure of the annual tree-ring growth from the 560-year average. This record indicates that the dry sequences range in length from as little as 6 years to as much as 43 years, with a median value of 15 years. The wet sequences are somewhat shorter, ranging from 4 to 24 years, with a median value of 12 years. On this basis the median cyclic base period would be about 27 years in length.

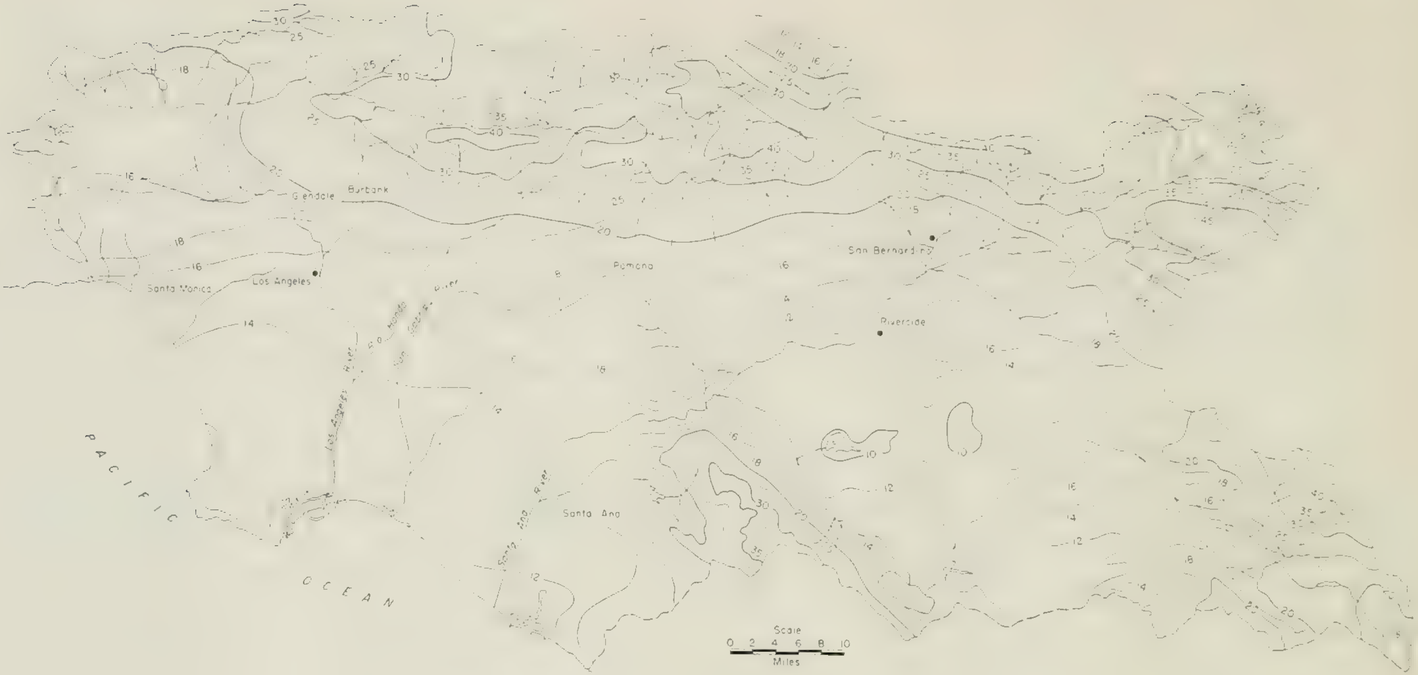

FIGURE 4. Areal distribution of average annual precipitation.

Areal Distribution. The effect of the very rugged terrain in the Los Angeles region on the passage of the incoming masses of moisture-laden air is to create a very irregular areal distribution of precipitation, as shown in figure 4. This map indicates that the average annual precipitaton ranges from 12 to 18 inches in the coastal plain, from 10 to 20 inches in the interior valleys, and reaches a maximum of more than 40 inches in the higher mountain areas. The region-wide average annual precipitation amounts to about 20 inches.

NATURAL WATER LOSS

Every living thing requires water for survival, and in such semi-arid areas as the Los Angeles region there always is keen competition for all the available water. In this competition, the vegetal cover tends to have the advantage because of its ability to utilize soil moisture, which is the most readily available and the best distributed form of water supply.

The water consumed by the native vegetation, whether in the undeveloped mountain and foothill areas or on the valley floor, together with the water evaporated from the leaves of the vegetative cover and from the land surface during or immediately following a storm, has been designated as "natural water loss." This natural water loss tends to consume the major part of the 20-inch basin-wide precipitation of the Los Angeles region. In fact, during many years the natural water loss consumes practically all of the precipitation, leaving only a small residuum available for other uses.

It is only in the higher mountain areas that the annual precipitation continuously exceeds the natural water loss. In such drainage areas as that of San Antonio Creek, where the altitude ranges from 3,400 to 10,080 feet, a basin-wide average annual precipitation of more than 40 inches produces a consistent surplus available for use in the valley-floor area below. Even in this drainage area, however,

Table 1. Average annual precipitation, recoverable water, and natural water loss, in inches, in the mountain tributaries of the Los Angeles region.

Drainage area [a]	Average altitude (feet)	Precipitation	Recoverable water	Natural water loss
San Antonio Creek near Claremont	6,700	41.8	18.9	22.9
Lytle Creek near Fontana	5,400	39.3	11.8	27.5
City Creek near Highland	3,800	34.8	7.8	27.0
Santa Ana River near Mentone	7,000	29.3	6.5	22.8
Lone Pine Creek near Keenbrook	4,700	26.2	1.5	24.7
Cajon Creek near Keenbrook	3,900	18.2	3.4	14.8

[a] Area above designated gaging station.

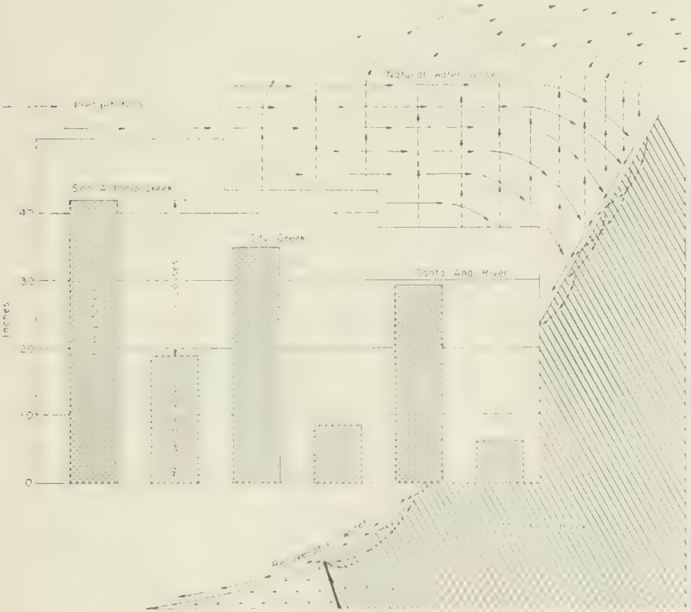

FIGURE 5. Precipitation, natural water loss, and recoverable water in three mountain basins.

the natural water loss consumes about 55 percent of the annual precipitation, as indicated in figure 5.

The amount of the natural water loss is determined by subtracting all the recoverable water (surface runoff plus or minus change in ground-water storage) from the basin-wide precipitation. The data included in table 1, opposite, are intended to supplement the records given in figure 5, and at the same time represent areas that have a wider range in altitude and precipitation. Among the six areas listed in this table, the average altitude ranges from 3,800 to 7,000 feet and the average precipitation from 18.2 to 41.8 inches. In all of these areas, except for Cajon Creek, the average annual natural water loss exceeds 20 inches.

RECOVERABLE WATER

All of man's water requirements for domestic, irrigational, and industrial purposes must be satisfied by this all-important differential between precipitation and the natural water loss. This supply cannot be increased unless the natural water loss can be reduced or water can be imported from sources outside the region.

Annual Distribution of the Runoff. Both the magnitude of the annual surface runoff and the recharge to ground-water storage are closely associated with the precipitation. In fact, both these items, being residuals, are even more variable than the precipitation. The 57-year record of annual runoff of the San Gabriel River near Azusa, given in figure 6, illustrates the extreme variability in the Los Angeles region. In this relatively short-time period, the annual runoff ranges from about 10,000 acre-feet in 1899 to 410,000 acre-feet in 1922, with an average of 115,000 acre-feet for the entire period.

This record contains three sequences in which the dry years tend to predominate and two sequences in which the wet years predominate. The average runoff for each of these sequences is given along the upper edge of the diagram. Then, combining these wet and dry sequences into unbiased basic periods, the average annual runoff will range from 112,000 to 129,000 acre-feet, as shown in the following table and in the lower part of figure 6.

Table 2. Average annual runoff, in acre-feet, of San Gabriel River near Azusa, California, for basic periods.

Basic period	Average runoff
1896-1922	129,000
1905-1936	125,000
1923-1944	112,000
1937-1951	129,000

Areal Distribution of Runoff. The distribution of annual runoff described above is typical of the annual distribution of the runoff throughout the Los Angeles region. On the basis of many records like that for the San Gabriel River near Azusa, it has been possible

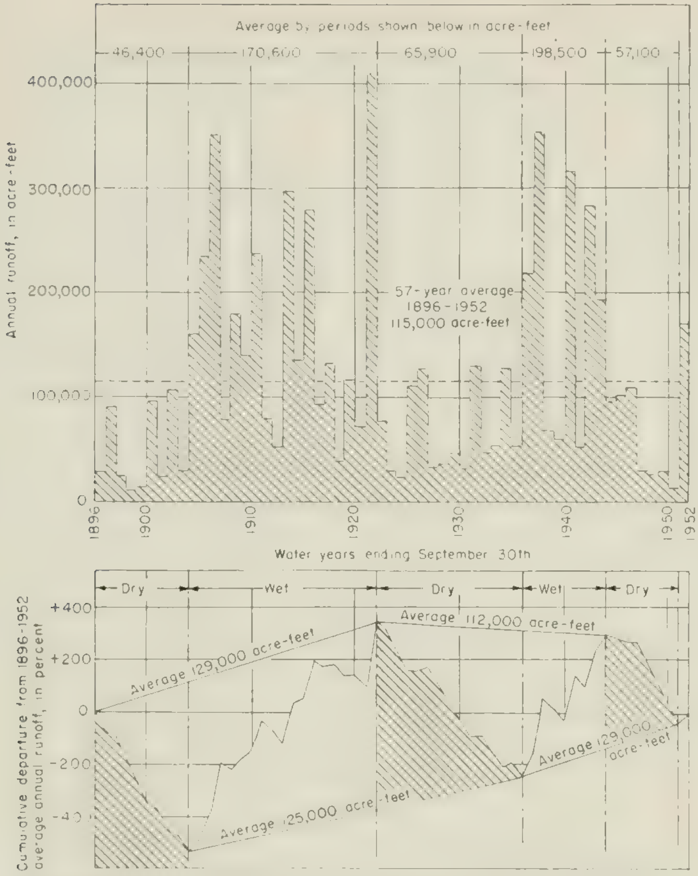

FIGURE 6. Annual runoff of San Gabriel River near Azusa, California, for the period 1896 to 1952.

to determine the areal distribution of the runoff throughout the region, as shown in figure 7.

This runoff is, of course, the residual of the precipitation whose distribution is shown in figure 4, after modification by the physiography of the area, the absorptive and retentive qualities of the mantle rock, and the natural water loss. Because of this multitude of influences, the average annual runoff ranges from less than 0.25 inch in the valley-floor areas to as much as 20 inches in the higher mountain areas.

Recharge to Ground Water. The runoff indicated in figure 7 represents only a part of the recoverable water in the Los Angeles region. Part of the precipitation, after entering the mantle rock and satisfying the soil-moisture deficiencies in the root zone of the vegetative cover, penetrates below the root zone into ground-water storage. In the fall, just prior to the winter rainy season, these soil-moisture deficiencies may range from as little as 2 inches in the frequently irrigated citrus areas to more than 18 inches in the areas that are covered by chaparral, or native brush. Muckel and Aronovici (1948) estimated that the average annual penetration below the root zone from precipitation in the Chino basin of the upper Santa Ana Valley amounted to 4.5 inches for the 20-year period of 1927-47. On this basis, the average annual deep penetration throughout the valley-floor areas of the Los Angeles region may be in the order of 250,000 acre-feet.

The ground-water storage is further recharged by the natural absorption of surface runoff along the bottoms of stream channels in the alluvial valley-floor areas, where the water table is well below the streambed. The average recharge from this source is estimated to be in the order of 350,000 acre-feet per year in this region.

Total Average Annual Recoverable Water. A reliable estimate of the total average annual recoverable water is extremely difficult to obtain at this time. Many important factors and influences affecting this water supply are not readily susceptible to direct observation, although a few others can be determined with reasonable accuracy. Included among these last are annual precipitation in the mountain and valley-floor areas, together with the runoff from the mountain areas and the natural runoff into the ocean, all of which

Table 3. Estimated annual recoverable water, in acre-feet, in the Los Angeles region.

	1923-34 Dry period	1935-44 Wet period	1945-51 Dry period
Mountain and foothill areas			
Precipitation	2,600,000	3,600,000	2,500,000
Natural water loss	−2,310,000	−2,860,000	−2,230,000
Valley floor area			
Precipitation	1,500,000	2,300,000	1,300,000
Unrecoverable natural water losses, such as interception and evaporation from the soil	−500,000	−500,000	−500,000
Soil moisture available to agricultural crops and native vegetation	−760,000	−1,070,000	650,000
Waste to ocean	80,000	300,000	−110,000
Annual recoverable water	450,000	1,170,000	310,000
Average annual recoverable water for basic periods		780,000	820,000

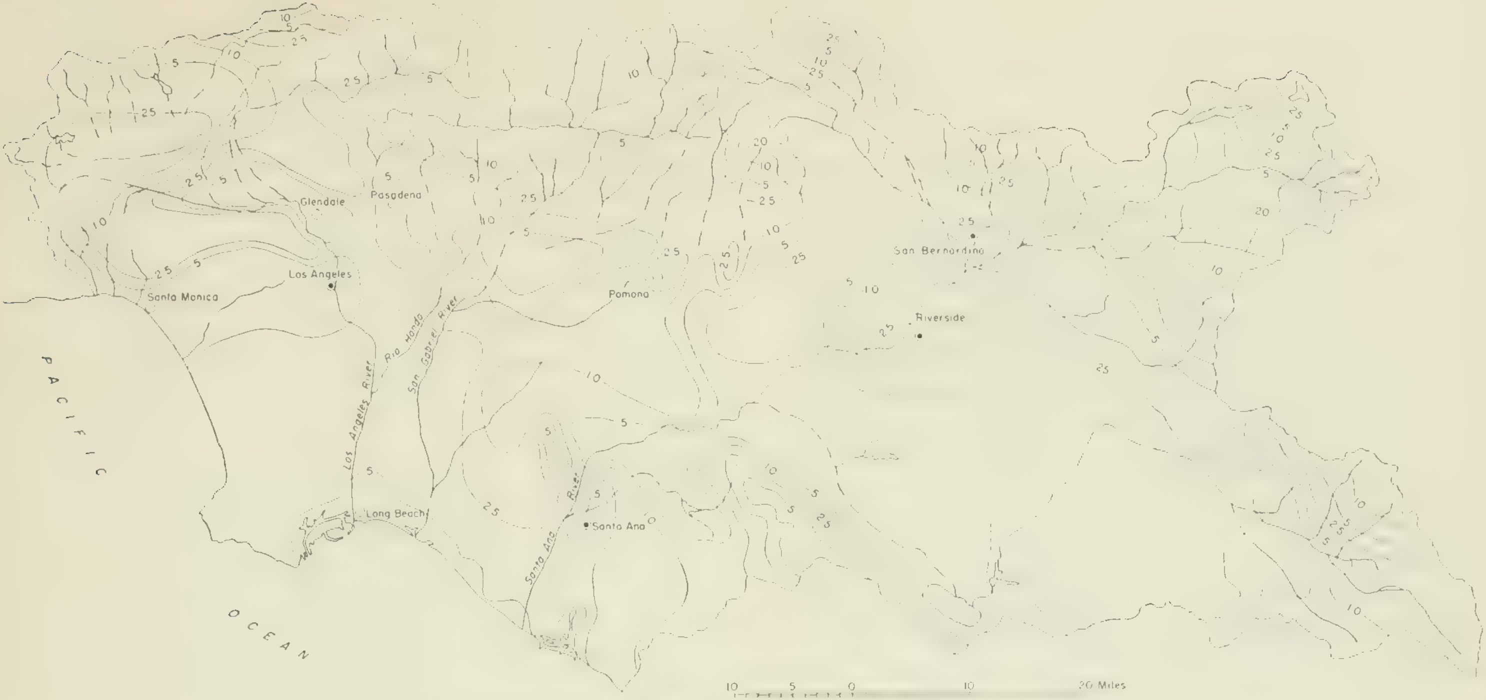

FIGURE 7. Areal distribution of average annual runoff.

are shown in figure 8. These data are presented for the two dry periods and one wet period extending from 1923 to 1951.

On the basis of these data, it has been possible to prepare the following table in which the average annual amount of recoverable water is determined for the unbiased basic periods of 1923-44 and 1935-51. The precipitation and runoff items in this table are obtained directly from figure 8. The natural water loss in the mountain and foothill areas is the difference between the precipitation and runoff from that diagram, ignoring any change in mountain and foothill ground-water storage. The unrecoverable natural water loss in the valley-floor area was estimated as equivalent to about 4 inches per year over the area. The soil moisture available to agricultural crops and native vegetation was determined on the basis of the soil-moisture deficiences in the fall, together with the winter consumptive use of the various plant types.

The average annual recoverable water for the Los Angeles region amounted to 780,000 acre-feet for the period 1923-44, and to 820,000 acre-feet for the period 1935-51. On the basis of these two periods, the regional average annual recoverable water amounts to about 800,000 acre-feet. This represents a measure of estimated safe yield of both the surface and ground-water resources of the Los Angeles region. When the annual water demands placed on these local reserves continuously exceed 800,000 acre-feet, then the resources are overdeveloped.

Because of the increasing population and attendant water requirements in southern California, it has been necessary to import water from the Owens Valley since 1913 and from the Colorado River since 1942. By 1951 the annual importations into the Los Angeles region from these two sources amounted to more than 400,000 acre-feet. In view of the 1,400,000-acre-foot water requirement of 1950,

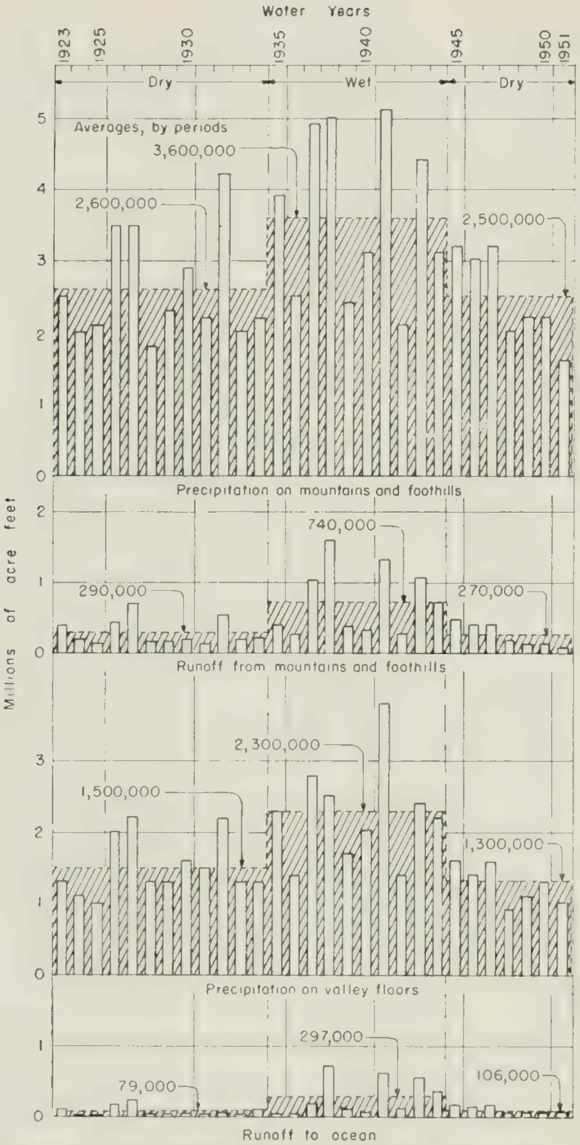

FIGURE 8. Annual precipitation and runoff in the Los Angeles region.

it is evident that the local water reserves are being depleted, or overdrawn, perhaps at a rate of as much as 200,000 acre-feet per year.

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2. HYDROLOGY OF THE MOJAVE DESERT*

By Harold C. Troxell † and Walter Hofmann †

The Mojave Desert is the large interior region that lies east of the Sierra Nevada and Tehachapi Ranges and north of the San Gabriel and San Bernardino Mountains. The northern and eastern limits of this arid region are not so well defined, and as a result its area ranges from 22,000 to 28,000 square miles, depending upon the location of these uncertain boundaries. This expanse of desert represents more than 14 percent of California's land area, but is very sparsely populated. It is about half the size of the State of New York, and is larger than 9 of the 48 states. Most of it lies within San Bernardino County, and smaller portions of it are in Inyo, Kern, Los Angeles, and Riverside Counties.

Climate. Climate is the result of the world-wide circulation of the earth's atmosphere, and is governed by a complex interrelationship among such meteorological factors as precipitation, temperature, humidity, sunshine, cloudiness, and wind.

As indicated in the preceding paper (Contribution 1), most of southern California's precipitation has its origin in the Pacific maritime air masses. The eastward and northeastward movement of these incoming air masses generally is blocked by the 5,000- to 11,000-foot mountain barriers that form the western and southern boundaries of the Mojave Desert region. The remnants of these air masses, after passing over the mountain divides, encounter few additional barriers to their continued movement. Consequently, there are few influences that tend to lower the air temperature and thereby cause condensation and precipitation. Indeed, the reverse is generally true, as these air masses, after passing the divides, tend to descend to lower altitudes. As a result, they become progressively warmer and develop evaporative characteristics.

Owing in part to the absence of cloudiness, wide ranges in temperature are characteristic of the Mojave Desert. Maximum temperatures of more than 100 degrees (Fahrenheit) are very common, and they are more than 130 degrees in some areas. Minimum temperatures are as low as 10 to 15 degrees during the winter months.

The desert area is noted for its low humidity. Seldom does the relative humidity exceed 60 percent, and average values range from about 30 to 40 percent. During the heat of the day, these values frequently decline to less than 10 percent.

Because of the deficient precipitation, the high air temperatures, and the low humidities, the climate of this region is classified as "arid."

Precipitation. The records from two representative stations at Bagdad and Yucca Grove have been used in developing the typical monthly precipitation diagram shown in figure 1. The records obtained at Bagdad, with its average annual precipitation of 2.24 inches, and at Yucca Grove, with its average annual precipitation of 6.88 inches, are intended to represent the extremes in precipitation on the desert.

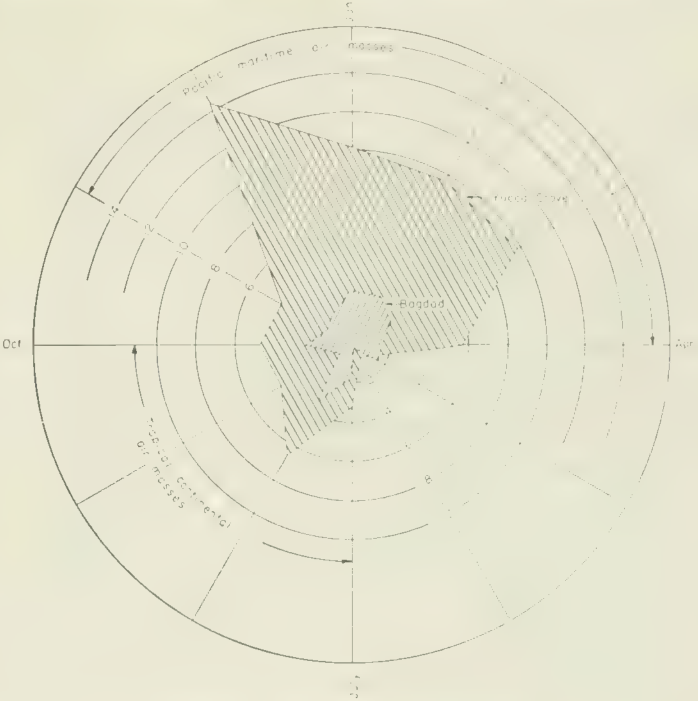

Figure 1. Typical monthly precipitation.

It is evident from a mere glance at this diagram that the major part of the annual precipitation occurs during the period of November through April. The storms during this 6-month period result from Pacific maritime air masses, and account for 54 percent of the meager precipitation at Bagdad and 72 percent of the precipitation at Yucca Grove.

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A second part of the annual precipitation occurs during the 4-month period of July through October. The storms of this period are largely the result of tropical continental air masses that generally originate in northeastern Mexico, western Texas, or New Mexico. The storms of this type are characterized by very intense rates of rainfall, which in general greatly exceed the rates of precipitation during the winter period.

As in most areas of meager precipitation, a single storm often represents essentially all the rainfall occuring within that month, and occasionally within the entire year. Because of this characteristic, desert precipitation tends to be highly variable with reference to time and place. Consequently, the areal distribution of the annual precipitation is extremely difficult to determine and lacks the uniformity generally associated with the coastal areas. The cyclic time distribution of the precipitation into wet and dry periods, such as that indicated for the Los Angeles region, is very much less evident in the Mojave Desert.

The typical variability of desert precipitation is shown in figure 2, in the form of a frequency distribution diagram. This diagram has been developed from the 38-year record obtained at Mojave between 1876 and 1914, and from the 32-year record obtained at Trona between 1920 and 1952. Both of these stations are in the western part of the desert. The average annual precipitation is 4.84 inches at Mojave and 4.12 inches at Trona. The frequency has been computed on the basis of a duration series in which a recurrence interval equal to twice the length of the period of record is assigned to the lowest annual precipitation observed during the period of record. The frequency scale is given in both percent of time and recurrence intervals in years. For values of annual precipitation greater than the median, these scales give the recurrence intervals and percent of time in which the annual precipitation is equal to or greater than that indicated by the curve. For values of annual precipitation less than the median, the reverse is true.

As shown by this diagram, the event becomes less frequent as the distance increases from the median, and the values located at equal distances from the median have the same frequency. The extreme values on this curve indicate that once in 100 years the annual precipitation can be expected to equal or exceed 2.7 times or 270 percent of the average annual precipitation, or can be expected to equal or be less than 0.03 times or 3 percent of the average annual precipitation.

The areal distribution of the average annual precipitation over the major part of the Mojave Desert is given in figure 3. The average values used in developing this map are based on the 72-year period of July 1880 to June 1952, and all the shorter records have been adjusted to this base period by means of precipitation indices. Except for the western and southern fringes of the desert, the average annual precipitation generally ranges from 3 to 5 inches in the valley-floor areas, and increases to more than 8 inches in some of the interior mountain areas.

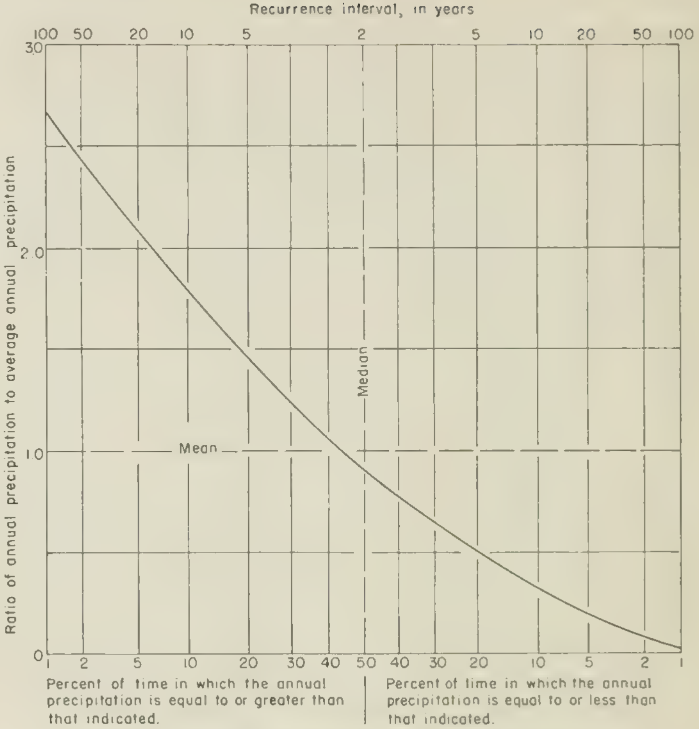

FIGURE 2. Typical frequency distribution of annual precipitation.

Runoff. An estimate of the runoff from this desert region is very much more complicated and difficult to obtain than the areal distribution of the precipitation. This is largely because the runoff is a precipitation residual that is affected by the rates of precipitation, the physiography of the area, the absorptive and retentive characteristics of the mantle rock, and any soil-moisture deficiency that may exist prior to each storm. Because of the intermittent nature of the runoff and the general inaccessibility of the desert areas, very little information of this nature is now available. In fact, existing

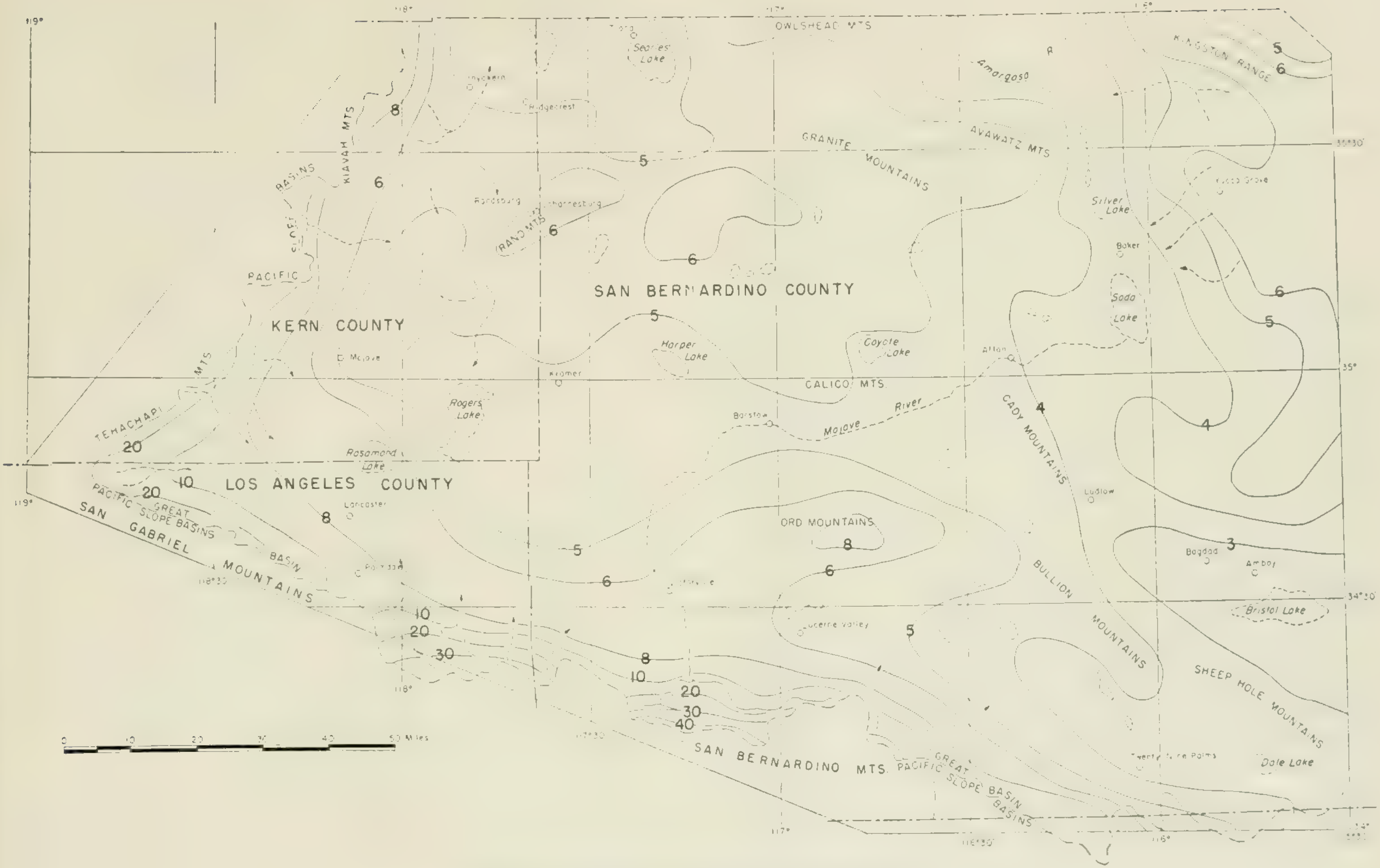

FIGURE 3. Areal distribution of average annual precipitation.

gaging stations are restricted to the Mojave River, Rock Creek, and Little Rock Creek, which drain areas of high precipitation in the San Bernardino and San Gabriel Mountains.

The Mojave River is by far the most prominent stream of the entire Mojave Desert region. Although its basin has an area of 4,900 square miles, only the 212-square-mile portion in the San Bernardino Mountains can be considered as a contributing area. This mountain portion of the basin has discharged annually about 82,000 acre-feet out onto the alluvial valley fill at the mouth of the canyon during the 47-year period of 1904 to 1951. This average annual runoff, equivalent to 1 foot of water over an 82,000-acre field, exceeds the average runoff of the Santa Ana River near Mentone by 18,000 acre-feet, and is only 32,000 acre-feet less than the average runoff of the San Gabriel River near Azusa. These last two streams are the most important sources of surface runoff in the Los Angeles region.

Because of the extreme variability of the precipitation in the San Bernardino Mountains, the annual runoff from the mountain areas of the Mojave River has ranged from as little as 4,340 acre-feet in the 1951 water year to as much as 345,000 acre-feet in the 1922 water year. During the drier years all the runoff, upon discharging from the mountain canyon, is quickly absorbed into the deep alluvial deposits of the valley-floor area within a distance of 1 or 2 miles. In contrast, during the flood period of March 1938 there was continuous flow out onto the desert for a distance of more than 110 miles; this flow passed Victorville, Barstow, and ancient Camp Cady, and debouched onto the dry playas of Soda and Silver Lakes near Baker.

A simple demonstration of the extreme variability and concentrated nature of this runoff is shown in figure 4.

This diagram, based on daily discharge of the Mojave River, shows that 50 percent of the runoff during the 47-year period of 1904 to 1951 has occurred in 3 percent of the time, or the equivalent of 3 days in 100, and 90 percent of the runoff has occurred in 23 percent of the time, or 23 days on 100. As a consequence, flow during the remaining 77 days in 100, or 77 percent of the time, delivers a mere 10 percent of the total runoff. This volume distribution is believed to be typical of all the streams in the San Gabriel, San Bernardino, and Tehachapi Mountains that are tributary to the Mojave Desert.

The much smaller precipitation by storms and their less frequent occurrence in the rugged interior mountain ranges of the desert tend to produce very much less runoff. In most of these mountain ranges such as the Bullion, Calico, Cady, Granite, Ord, and many others, the average annual precipitation is less than 5 to 6 inches. It is estimated that only in a very few areas does the average annual runoff from these mountains exceed 0.2 inch. This runoff is likely to be even more concentrated than the precipitation with reference to time, with about 50 percent of the volume occurring in about 1 day in 1,000, and 90 percent of the volume in about 1 day in 100. Most of this very infrequent storm runoff is absorbed into the alluvial fans at the mouths of the canyons, and very little of it reaches the playas in the bottoms of the valleys.

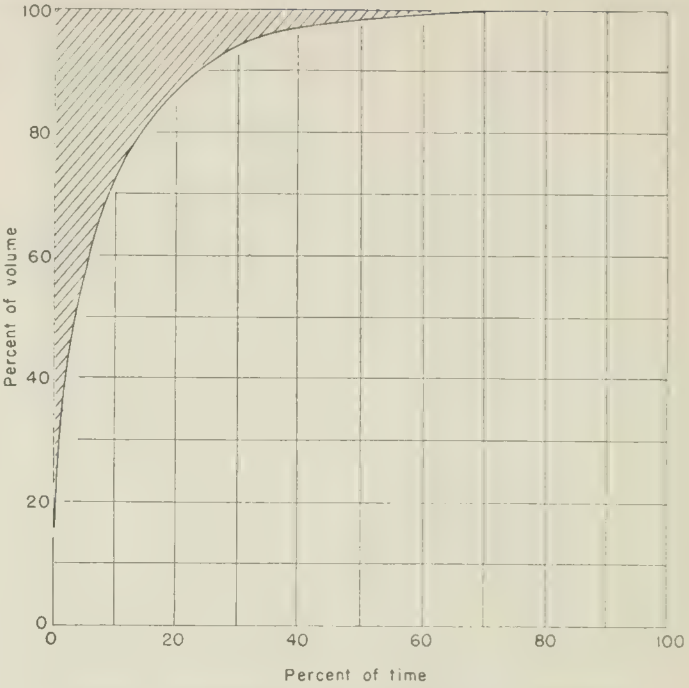

FIGURE 4. Relationship between time and volume of runoff in the Mojave River basin.

Ground Water. Except for a few springs in the mountain areas, practically all the water reserves of the Mojave Desert are stored as ground-water in the deep alluvial fills of the valleys. These reserves are sustained almost entirely from runoff originating in the rugged mountain portions of the desert. As a consequence, the recharge to these reserves varies considerably, both with time and on an areal basis.

The largest single source of recharge to the water reserves of the Mojave Desert is the Mojave River. During the last 47-year period, this mountain stream has delivered an average annual runoff of 82,000 acre-feet to the alluvial valley-floor areas, of which 92 percent, or 75,000 acre-feet, was retained between the mountains and Afton (downstream from Barstow), largely as a recharge to groundwater storage. The magnitude of this recharge varies considerably, and is dependent on the limitations of the various subbasins along this 95-mile channel.

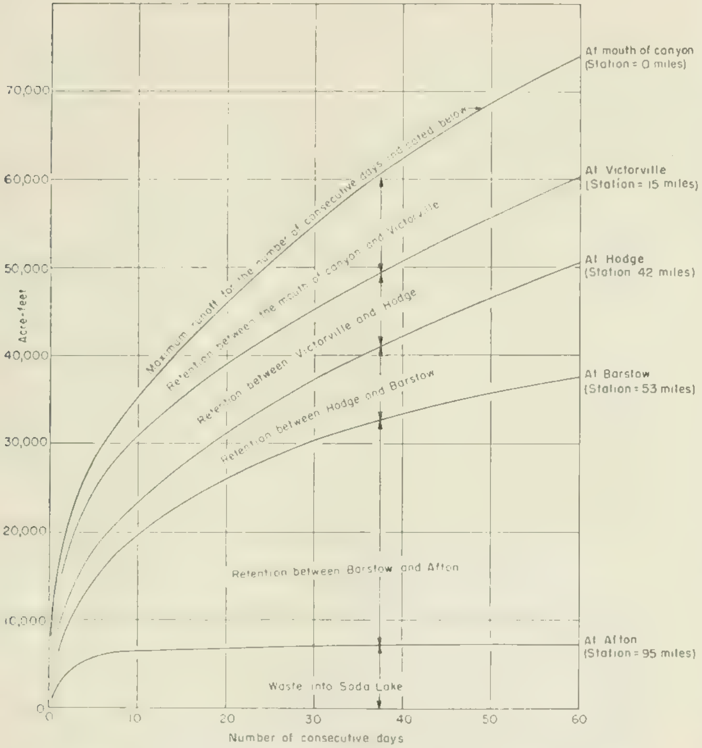

FIGURE 5. Runoff and retention in the Mojave River basin for the 60 consecutive days of greatest runoff in 1932.

The magnitude and character of the retention, during the 60 consecutive days of maximum runoff in 1932, are shown for certain subbasins in figure 5. During that year, gaging stations were operated at the mouth of the canyon, at Victorville about 15 miles from the mountains, at Hodge about 42 miles, at Barstow about 53 miles, and at Afton about 95 miles from the mountains. The purpose of the diagram is to show the maximum retention and its time distribution between these stations for the periods of maximum runoff ranging from 1 to 60 consecutive days. During this 60-day period in February, March, and April 1932, only 7,200 acre-feet of the 74,000 acre-feet leaving the mountain area were wasted as surface flow past Afton. The largest amount of the retention occurred between Barstow and Afton, where a retention of about 9,000 acre-feet during the maximum 5-day period increased to 30,000 acre-feet for the maximum 60-day period. On a unit basis, this retention would decrease from 43 acre-feet per day per mile of channel for the maximum 5-day period to 12 acre-feet per day per mile of channel for the 60-day period.

In the uppermost basin, between the mountains and Victorville, a retention of 3,000 acre-feet for the maximum 5-day period increased to 13,000 acre-feet for the maximum 60-day period. In this basin, the retention of 40 acre-feet per day per mile of channel for the first period decreased to 14 acre-feet per day per mile of channel for the second period.

In contrast, the smaller subbasin between Victorville and Hodge is believed to have been largely recharged during the maximum 5 days of the storm period, as the additional 55 days of runoff appeared to add only 40 percent to the retention.

These basin recharge characteristics, however, are not believed to be typical of all of the many ground-water basins and subbasins that cover the vast interior portions of the Mojave Desert. Unfortunately, very little is known as to maginitude of the average annual recharge in most of this interior area.

Water Utilization. Because of the general need for agricultural crops and more "living space" in southern California, there has been a steady increase in the development and occupation of the desert regions. In some of the more favorably located areas, such as Antelope Valley, the water reserves are being depleted at an alarming rate. As a consequence, the water levels near Lancaster have declined about 100 feet during the last 30 years. This clearly indicates that this general area currently is being overdeveloped, and that water reserves are being drawn upon without satisfactory means of replenishment.

Except for the few more favored areas of substantial supply, the opportunity for replenishment of reserves is meager. Thus, with continued development of the desert and expansion of the population now moving to the desert, the utilization of ground-water reserves is likely to become a typical desert problem just as it now is in the Antelope Valley area.

3. GEOLOGY AND HYDROLOGY OF VENTURA COUNTY

By R. G. Thomas,[1] E. C. Marliave,[2] L. B. James,[3] and R. T. Bean [3]

INTRODUCTION

This paper is an extract from a lengthier and more detailed report entitled "Ventura County Investigation," that was released in 1953 as Bulletin No. 12 of the California State Water Resources Board.[4]

Data of considerable value in the interpretation of the geology and ground-water hydrology of the region were made available by the following agencies and organizations: Ground Water Branch, Geological Survey, U. S. Department of Interior; Soil Conservation Service, U. S. Department of Agriculture; Office of Public Works, U. S. Naval Construction Battalion Center, U. S. Naval Advanced Base Depot, Port Hueneme; Office of Public Works, Point Mugu Air Missile Test Center; California Department of Natural Resources, Division of Oil and Gas and Division of Mines; Ventura County Water Survey; Santa Clara Water Conservation District; City of Ventura Water Department; Standard Oil Company of California; General Petroleum Corporation; Superior Oil Company.

In addition, the following individuals have contributed helpful criticisms and suggestions during the course of the investigation: Thomas L. Bailey, consulting geologist; Frank Bell, Shell Oil Company; Harold Conkling, consulting engineer; K. O. Emery, University of Southern California; Spencer Fine, Richfield Oil Company; Edward Hall, Union Oil Company; Robert F. Herron, M. J. M. & M. Oil Company; John F. Mann, consulting geologist; Wm. R. Merrill, Standard Oil Company; Henry H. Neel, Tide Water Associated Oil Company; Robert Paschall, Amerada Petroleum Corporation; F. P. Shepard, Scripps Institute of Oceanography; Edward L. Winterer, U. S. Geological Survey.

The assistance of all of the above organizations and individuals, as well as numerous other geologists, landowners, well drillers, and individuals, is gratefully acknowledged.

GENERAL GEOLOGIC FEATURES

Geomorphology. Much of Ventura County is marked by rugged, maturely dissected mountains that rise in many places to altitudes of 6,000 feet or more. Valleys of various sizes are present within the mountainous areas, and a broad coastal plain lies southeast of the city of Ventura (pl. 1). Most of the ranges and valleys are distinctly longitudinal, and trend east in general conformity with the grain of the Transverse Range province. The northern part of the county, in contrast, lies in the Coast Range province, where the topographic and structural grain has a northwesterly trend.

Some of the valleys are defined by structural features in the underlying bedrock, whereas others lie athwart these features. The Santa Clara River Valley occupies the axial part of a large basin of Cenozoic sedimentation, and in part represents a broad area that has been depressed along major east-west faults. The Ventura River Valley is primarily erosional, and Ojai and Simi Valleys are essentially structural depressions (pl. 2). The coastal plain area is occupied by an apron of sediments contributed by the Santa Clara River and other streams that drain the ajacent highland areas.

Offshore topography, as determined by the U. S. Coast and Geodetic Survey, is shown in plate 3. This area recently has been described and discussed by Emery and Shepard (1945), and by Emery and Rittenberg (1952). Anacapa, Santa Rosa, and Santa Cruz Islands are high parts of an elongate ridge that is the westerly extension of the Santa Monica Mountains, which form the southern margin of the Transverse Ranges province. The scarplike southern face of these mountains extends out to sea, where it is cut by the southward trending Hueneme and Mugu submarine canyons. The heads of these two canyons lie within a quarter of a mile of the shore. Water-bearing strata undoubtedly are exposed along their walls, and hence are in contact with sea water (pl. 3). This contact is very important in considering the movements of ground-water, inasmuch as fresh water can be discharged into the ocean or sea water can move into the aquifers, depending upon the direction of the ground-water gradient.

Stratigraphy. The rocks of Ventura County consist of a pre-Cretaceous "basement" of igneous and metamorphic types, a thick section of Cretaceous and Cenozoic sediments, and locally abundant Tertiary volcanic rocks (pl. 2). The sedimentary section includes a great number of rock types, most of which are marine and nearly all of which are clastic. The volcanic rocks represent flows, pyroclastic accumulations, and shallow intrusive masses. Descriptions of the various formations are included in plate 2. Most of the older rocks are well indurated, and can be considered as essentially nonwater-bearing; in effect they form the basins that contain the younger and more permeable water-bearing formations.

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[2] Supervising Engineering Geologist, California Division of Water Resources, Sacramento.

[3] Senior Engineering Geologist, California Division of Water Resources, Sacramento.

[4] Bulletin 12 contains an inventory of the underground and surface water resources of Ventura County, estimates of present and ultimate water utilization, estimates of present and ultimate supplemental water requirements, and preliminary plans and cost estimates for local water-development works and works for importing water from sources outside the county. It summarizes an investigation that was conducted under the joint auspices of the State Water Resources Board, the County of Ventura, and the Department of Public Works acting through the agency of the State Engineer.

The most important water-bearing formations in Ventura County comprise sedimentary strata of Pleistocene and Recent age. The oldest of these is the Santa Barbara formation, which is uppermost Pliocene and lowermost Pleistocene in age. It ranges from about 4,000 feet of mudstone, shale, and minor sandstone near the city of Ventura to about 1,000 feet of sand, gravel, and minor clay in the Tapo Canyon area and 800 feet of sand and clay beneath the southern part of the Oxnard Plain. As the lithologic variations might suggest, the permeability of the Santa Barbara formation also is extremely variable. In places its upper part contains a zone of highly permeable sand and gravel that is known as the Grimes Canyon member. This zone contains fresh water of good quality in the Las Posas and Pleasant Valley areas. The stratigraphic and structural relationships of the Grimes Canyon member in typical areas are shown in the geologic sections (pls. 6, 7).

The San Pedro formation, of early Pleistocene age, overlies the Santa Barbara formation. It consists of as much as 4,000 feet of marine and terrestrial gravel, sand, and clay, and yields water to wells in the Santa Clara River Valley and in the Las Posas, Oxnard Plain, and Pleasant Valley areas. As far as is now known, all water in the San Pedro gravels and sands is of good quality except that below depths of about 2,000 feet in the Santa Clara River area, where a few electric logs indicate that the water may be slightly brackish. A prominent zone of marine sand and gravel, about 300 feet in maximum thickness, lies at or near the base of the formation. It is herein referred to as the Fox Canyon member. It is a prominent aquifer on the south side of Oak Ridge and beneath the Las Posas area (pls. 6, 7).

Sands, gravels, and clays of late Pleistocene age extend from the top of the San Pedro formation upward to the base of the Recent alluvium. These sediments are undisturbed to gently folded, in contrast to the much more deformed San Pedro and older formations. The upper Pleistocene sediments yield water to wells in several parts of the county, including the Pleasant Valley area, Simi and Ojai Valleys, and the Santa Clara River Valley. The principal aquifer beneath the Oxnard Plain is a stream-deposited gravel of late Pleistocene age which is términed the Oxnard aquifer in this paper (pl. 6).

Recent alluvium is thin in most of the valley areas of Ventura County, and probably is nowhere more than 60 or 70 feet thick. It consists of sand, gravel, and clay. Except in areas where the water table is high, most wells obtain water from materials that lie beneath this.

Structure. Most of the major faults and other structural elements in all but the northern part of Ventura County have the east trend that is characteristic of the Transverse Range province. In detail, however, the faults within the county can be divided into northwest-trending, northeast-trending, and east-trending families. Displacements along some of the faults have been essentially strike-slip and along others essentially dip-slip, but both components of movement are represented along most of them. In addition to the major faults shown on the geologic map (pl. 2), great numbers of minor faults also are present. Nearly all of the faults actually are zones of faulting, rather than single sharp breaks, and the widths of the zones generally are greater on the faults of larger displacements. The San Andreas fault, probably the best known fault in California, crosses the extreme northeastern corner of the county.

Faults and accompanying folds affect ground-water in a variety of additional ways, such as by changing cross-sectional area of permeable strata and by exposing permeable strata to erosion and infiltration by surface waters. Some of the faults may be conduits along which deep waters of poor quality migrate toward the surface. Faults that may be of this type include the Hot Springs and Santa Ynez, and possibly the San Cayetano and Oak Ridge faults (pl. 2). Evidence of upward movement of deep waters appears in the analyses of water from some springs and of some ground-water from alluvium near faults. The principal faults in the county that are known to have a barrier effect on ground-water are the Saticoy and Springville faults and a portion of the Camarillo fault (pl. 2).

Nearly all of the stratified rocks in this region have been folded. The folds that are most significant from the standpoint of ground-water are the Santa Clara River syncline, the Montalvo anticline, and the several folds in the synclinal area south of Oak Ridge. The Santa Clara River syncline extends from the ocean up the Santa Clara River Valley into Los Angeles County. The permeable San Pedro formation has been folded in this syncline, and is exposed on its north flank from the ocean to a point about 3 miles east of Santa Paula. These beds thus can be recharged by rainfall penetration and stream infiltration. Similar relations may exist on the south flank of the syncline, but here the beds are covered by alluvium along the bed of the Santa Clara River, and also are partly concealed by older formations that have been thrust up along the Oak Ridge fault (pl. 5).

The Montalvo anticline extends from the ocean up the south side of the Santa Clara River Valley. The trace of its axial plane crosses the river near Montalvo, and continues eastward south of the Saticoy fault. Although the structure of this anticline is not simple, it seems clear that the permeable San Pedro formation has been involved in the folding, and has since been eroded and covered by alluvial gravels in the Oxnard Forebay Basin (pl. 6). As a result, certain aquifers within this formation are believed to be in hydrologic continuity with ground-water in the overlying alluvium.

The folds from Oak Ridge south to the Las Posas area expose aquifers that can be recharged by surface waters, and these aquifers, where buried in other areas, can be reached by wells. Variations in storage probably occur in the Fox Canyon aquifer in different parts of the major anticlines, and in the synclinal areas ground-water generally is confined by overlying silts and clays.

GROUND-WATER STORAGE AND FLOW

Storage. During the investigation for the present report, changes in ground-water storage were estimated for the more important basins within Ventura County (pl. 4). This process involved a determination of the change in volume of saturated sediments that occurred over selected periods of study, and estimation of the percentage of this volume that contained extractable ground-water. These factors were obtained by computing the volume of sediments that lay between the respective water tables that existed at the start and close of the study period, and by evaluating the average weighted specific yield of the sediments between the water tables on the basis of available well logs. Storage changes over the periods of study were computed by multiplying changes in volume of saturated sediments by average weighted specific yield.

Values used for specific yield were slightly modified from those previously determined by the Division of Water Resources in an investigation of the South Coastal Basin (1934). The values used in the Ventura County Investigation are as follows:

Material	Specific yield (percent)
Soil, silty clay	3
Clay, adobe, "hard pan"	0
Clayey sand, sandy silt	5
Clayey gravel	7
Sand	25
Tight sand, cemented sand	18
Gravel, gravel and sand	21
Tight gravel, cemented gravel	14

Subsurface Flow. Two methods, the slope-area method and the rising-water method, were used to determine amounts of subsurface flow of ground-water at different locations within the county. The slope-area method involves the common form of Darcy's law, using the units proposed by Meinzer, $Q = PIA$. In this equation, Q is the subsurface flow in gallons per day passing through the cross-sectional area A measured in square feet; P is permeability in gallons per day per square foot of cross-sectional area (often called Meinzer units); and I is the slope of the water table at the cross section.

The rising-water method of computing subsurface flow is applicable where rising water (effluent seepage) occurs perennially and where the cross-sectional area of saturated sediments is unknown. The method has been noted by Tolman (1937, p. 491), and a variation of the method was used by Kimble (1936). It also is based on the formula $Q = PIA$, and is dependent on the variation at different times in the amount of perennial rising water with variation in the ground-water slope above the first appearance of rising water in a restricted filled channel. The formula is

$$Qu = \frac{I_1\ (Qr_2)\ - I_2\ (Qr_1)}{I_2 - I_1},$$

where Qu is the subsurface flow (constant), I_1 and I_2 the ground-water slopes, and Qr_1 and Qr_2 the amounts of rising water at times t_1 and t_2, respectively.

Rising-water measurements were used to compute subsurface flow between the basins along the Santa Clara River Valley by this method. In order to compute a subsurface flow under all conditions, it was necessary to estimate the decrease in flow when water levels in the basins were drawn down so far that rising water no longer occurred. To do this the logarithm of rising-water flow plus previously estimated subsurface flow was plotted against basin-storage depletion, and the relation was found to be nearly that of a straight line. This line was then projected past the point where zero rising water occurred, and the projected line was used to estimate subsurface flow and basin depletion for conditions of zero rising water.

Pump tests to determine permeability were conducted where possible. The recovery and drawdown methods were used, these methods depending, respectively, on time-rate of recovery after pumping is stopped, and on time-rate of drawdown during the pumping.

GROUND-WATER BASINS

Ground-water basins of Ventura County are shown in plate 4. They are grouped into three major hydrologic units, the Ventura, Santa Clara River, and Calleguas-Conejo, together with miscellaneous basins. The most important basins, so far as amount of water pumped and economic utilization are concerned, are those that are composed of unconsolidated sediments. In some of them the ground-water occurs in a single unconfined body, and in others it occurs in more than one aquifer. Water in some basins also occurs in volcanic rocks, and in parts of other basins it is abundant in fractures in consolidated sedimentary rocks.

Ventura Hydrologic Unit. Pertinent characteristics of the ground-water basins in the Ventura Hydrologic Unit (pl. 1) are shown in table 1.

Table 1. Summary of selected characteristics of ground-water basins in Ventura Hydrologic Unit.

Basin	Area, in acres	Estimated weighted average specific yield,* in percent	Water-bearing formations	Principal aquifers	Estimated depth from ground surface to base of aquifers, in feet	Estimated thickness of aquifers, in feet	Condition of occurrence of ground-water	Estimated average yield of irrigation wells, in gallons per minute
Upper Ojai	1,950	8	Recent and Pleistocene alluvium	Lenses of permeable sediments	0-300	0-300	Unconfined	50
Ojai	6,040	5.5	Recent and Pleistocene alluvium	Lenses of permeable sediments	0-700	0-700	Essentially unconfined; locally semi-confined	400
Upper Ventura River	4,990	8	Recent and Pleistocene alluvium	Sand and gravel beds	0-100	0-100	Unconfined	600
Lower Ventura River	2,670	8	Recent and Pleistocene alluvium	Sand and gravel beds	0-100	0-100	Unconfined	--

* In zone of historic water-level change.

The Upper Ojai basin is separated from other basins by Tertiary sediments that are relatively impervious, and there is little subsurface outflow. The usable storage capacity of the basin is small, and utilization of ground-water therein is minor at the present time. The principal sources of ground-water replenishment in this and other basins of Ventura County are deep penetration of precipitation, infiltration of surface water from streams, and infiltration of the unconsumed portion of water applied for irrigation and other uses. A minor source of replenishment is lateral movement from flanking Tertiary formations. Ground-water is depleted by pumped extractions, consumptive use of phreatophytes, effluent seepage into streams, and by some subsurface outflow into lower basins.

The Ojai basin is principally a free ground-water basin, but some wells in its southwestern part flow during periods of high water level. This basin is also essentially rimmed by consolidated, relatively impermeable formations except at its westerly end, but even there the mantle of alluvium is so thin that subsurface outflow to the Ventura River Basin is believed to be insignificant. There has been more development of ground-water for irrigation in the Ojai than in the Upper Ojai Basin. Total usable storage capacity of the Ojai Basin is estimated to be about 70,000 acre-feet.

The Upper and Lower Ventura River Basins are separated by a constriction, near Foster Park, at which a diversion weir is located. Development of ground-water resources is considerably greater in the upper than in the lower basin. The ground-water generally moves in the direction of the surface slope from the upper to the lower basin. A few wells in part of the Upper Ventura River Basin penetrate the full thickness of the Quaternary alluvium and draw some water from underlying sandstones and conglomerates of the Oligocene Sespe formation. Total storage capacity of the Upper Ventura River Basin is estimated to be about 10,000 acre-feet.

Few wells are present in the Lower Ventura River Basin, and estimates of storage capacity were not made because of the lack of meaningful data. Ground-water in the alluvium is believed to move approximately parallel to the river and to discharge into the sea. Strata of the San Pedro formation flank and underlie the alluvium near the mouth of Ventura River. They strike east and dip to the south, and are believed to be in hydrologic continuity with similar strata in the Mound Basin (pl. 4).

Santa Clara River Hydrologic Unit. The ground--water basins within the Santa Clara River Hydrologic Unit (pl. 1) include the Piru, Fillmore, Santa Paula, Mound, Oxnard Forebay, Oxnard Plain, and Pleasant Valley Basins, as shown in plate 4. The characteristics of these basins, the most productive in Ventura County, are summarized in table 2.

The structure of the Piru basin is shown in cross section in plate 5. The gravels and sands of the San Pedro formation underlie the younger alluvial deposits, but do not crop out in this basin. Wells draw water from both the San Pedro sediments and the alluvium. Ground-water movement in the basin is generally westward, and subsurface flow from the east probably is negligible because of the thin alluvial cover at the eastern boundary of the basin. The storage capacity to a depth of 1,000 feet is estimated to be about one million acre-feet, and subsurface flow out of this basin into the Fillmore Basin has been estimated by the rising-water method to be thirty second-feet at times when rising water is present.

With respect to both surface and subsurface drainage, the Fillmore Basin lies downstream from the Piru Basin. Both basins occupy the same fault-bounded syncline, but differ from each other in some structural details (pl. 5). The alluvium and the underlying San Pedro formation in the Fillmore Basin are reached by water wells, and the general movement of ground-water is downstream toward the Santa Paula Basin to the west. Subsurface outflow into the Santa

Table 2. Summary of selected characteristics of ground-water basins in Santa Clara River Hydrologic Unit.

Basin	Area, in acres	Estimated weighted average specific yield,* in percent	Water-bearing formations	Principal aquifers	Estimated depth from ground surface to base of aquifers, in feet	Estimated thickness of aquifers, in feet	Condition of occurrence of ground-water	Estimated average yield of irrigation wells, in gallons per minute
Piru	6,520	16.7	Recent and Pleistocene alluvium	Sand and gravel beds	0–200	0–200	Unconfined	800
			San Pedro formation	Sand and gravel beds	1,000+	800+	Unconfined	800
Fillmore	16,870	12.2	Recent and Pleistocene alluvium	Sand and gravel beds	0–250	0–250	Unconfined	700
			San Pedro formation	Sand and gravel beds	1,000+	750+	Unconfined	700
Santa Paula	13,520	10.0	Recent and Pleistocene alluvium	Lenses of permeable sediments	0–200	0–200	Essentially unconfined	700
			San Pedro formation	Lenses of permeable sediments	1,000+	800+	Essentially unconfined	700
Mound	12,300	----	San Pedro formation	Lenses of permeable sediments near top	1,500+	1,000+	Confined	700
Oxnard Forebay	6,170	16.5	Recent and Pleistocene alluvium	Most of formation	100–250	100–250	Unconfined	1,100
Oxnard Plain	46,460	----	Recent alluvium	Semi-perched water-bearing zone	0–50	0–50	Unconfined	--
			Upper Pleistocene alluvium	Oxnard aquifer	180–250	75–200	Confined	900
			San Pedro formation	Fox Canyon member	600–1,900	100–300	Confined	900
Pleasant Valley	23,850	----	Recent and Pleistocene alluvium	Permeable lenses not connected with Oxnard aquifer	0–400	--	Essentially confined	400
			San Pedro formation	Fox Canyon member	400–1,500	100–300	Confined	1,000

* In zone of historic water-level change.

Paula Basin has been estimated by the rising-water method to be about sixteen second-feet, and a reduction of this flow would be expected after rising water stops. Total storage capacity of the upper thousand feet of the Fillmore Basin, like that of the Piru Basin, is estimated to be about one million acre-feet.

The Santa Paula Basin is separated from the Fillmore Basin by a line arbitrarily placed near the point of greatest constriction in the valley and the estimated position of maximum rising water. The Santa Paula Basin is in turn bounded from the Mound Basin on the west by a steep gradient in the ground-water surface. This steep gradient is believed to be in part the result of a decrease in the permeability of sediments underlying the area, and in part the result of some minor faulting. The boundary between the Santa Paula Basin and the Oxnard Forebay Basin on the southwest (pl. 4) is determined in part by the position of the Saticoy fault and in part by the locus of points where surface water from the Santa Paula Basin begins to percolate into the river gravels.

The structure of the Santa Paula Basin is similar to that of the Fillmore Basin (pl. 5). It is synclinal, and is bounded on the south by the Oak Ridge fault. Ground-water occurs in both the alluvium and the underlying San Pedro formation. San Pedro strata crop out in an extensive area along the north side of the basin; they dip southward, and apparently are in hydrologic continuity with the San Pedro strata that lie beneath the alluvium farther south in the basin.

Ground-water in the Santa Paula Basin generally moves in a westerly direction. Total storage capacity of the basin is estimated to be about 800,000 acre-feet for an area of 10,000 acres and to a depth of about 800 feet. A pronounced barrier effect of the Saticoy fault between this basin and the Oxnard Forebay Basin is shown by a 50- to 100-foot difference in ground-water levels on the opposite sides of the break. Ground-water movement from the Santa Paula Basin into the Oxnard Forebay Basin has been estimated by the rising-water method to be ten second-feet. Geologic data necessary for an accurate estimate of subsurface outflow into the Mound Basin are lacking.

The principal water-bearing unit in the Mound Basin is the San Pedro formation. The structure of the basin is essentially synclinal, and the San Pedro formation also is folded in the Montalvo anticline and is displaced by the Saticoy fault. During periods of high water levels, a seaward gradient exists in the basin. When water levels are low, the gradient is reversed and sea-water intrusion may occur, although no evidence of deterioration in water quality has yet been found.

Replenishment of the ground-water in the Mound Basin occurs by subsurface inflow from the Santa Paula Basin and from the outcrop area of the San Pedro formation, where the principal contribution is from rainfall penetration and stream infiltration. Depletion is by pumped extractions and possibly by subsurface outflow. Little or no change in storage is estimated to occur within the Mound

Basin. Inasmuch as water-level and well-log data are lacking in the outcrop area of the San Pedro formation, changes in storage within the part of this unit that lies north of the basin could not be estimated, although such changes may be appreciable.

The Oxnard Forebay Basin is the free ground-water area or forebay that is in hydraulic continuity with the Oxnard Plain Basin (pls. 4, 6). Recent and upper Pleistocene alluvium is the most important water-bearing material in this basin. It is underlain unconformably by the San Pedro formation and, in a small area, by the Santa Barbara formation. The boundary between the Oxnard Forebay and Mound Basins has been placed along the north edge of the Santa Clara River, where well logs indicate the approximate northwestern limit of permeable gravels in the alluvium.

Ground-water in the Oxnard Forebay Basin moves southwestward toward the Oxnard Plain Basin (pl. 8). Subsurface inflow to the Oxnard Forebay Basin is from the Santa Paula Basin through and possibly over the Saticoy fault. Some subsurface inflow may be derived from the Mound Basin when water levels there are higher than in the Oxnard Forebay Basin. Subsurface outflow into the pressure aquifers of the Oxnard Plain Basin and possibly into those of the Pleasant Valley Basin takes place through strata of the San Pedro formation, primarily the Fox Canyon Member. At times, some subsurface outflow into the Mound Basin probably occurs through the San Pedro formation in the area near Montalvo. When water levels in the Oxnard Forebay Basin are above the clay cap of the Oxnard Plain Basin, some subsurface outflow may occur into the semiperched zone that lies above the clay cap (pl. 8).

Estimated total storage capacity of the alluvium in the Oxnard Forebay Basin is about 300,000 acre-feet. If water levels were drawn down so that the Oxnard aquifer was completely dewatered, the total available storage capacity of the Oxnard aquifer in the Oxnard Plain and Oxnard Forebay Basins probably would be of the order of 800,000 acre-feet.

The Oxnard Plain Basin includes about one-fourth of the irrigated area of Ventura County. The principal formations and aquifers underlying this basin are shown in plate 6. The most important water-bearing unit is the Oxnard aquifer, a series of upper Pleistocene river-deposited gravels that are continuous with gravels in the Oxnard Forebay Basin. The boundaries between the Oxnard Plain Basin and the Mound and Pleasant Valley Basins coincide with the limits of the Oxnard aquifer in those directions. The boundary between the Oxnard Forebay and Oxnard Plain Basins is placed to include in the Oxnard Plain Basin the area where applied water does not return to the principal aquifers.

Although well-log control for the sediments beneath the Oxnard aquifer is poor, available data indicate that other aquifers of unknown areal extent and hydrologic continuity exist between the Oxnard aquifer and the Fox Canyon aquifer. In the southeast part of the Oxnard Plain Basin, a fairly continuous gravel stratum approximately 70 feet thick occurs at a depth of about 400 feet and extends at least partly into the Pleasant Valley Basin.

The Recent and Upper Pleistocene alluvium is underlain by the San Pedro formation, which ranges in thickness from about 600 feet in the southern part of the Oxnard Plain to about 1,800 feet just south of the Santa Clara River. Only two water wells in the Oxnard Plain are known to penetrate the entire thickness of the San Pedro formation. Available oil-well logs, electric logs, and water-well logs indicate that the Fox Canyon member, at the base of the San Pedro formation, is a potentially important aquifer in the Oxnard Plain Basin (pl. 6). The Santa Barbara formation underlies the San Pedro formation beneath the Oxnard Plain, and probably contains water that is slightly brackish to definitely poor in quality.

The water-bearing materials of the Oxnard Plain Basin in general are nearly horizontal and are not known to have been affected by faulting. The structure of this basin is shown in plate 6. Both the Oxnard and Fox Canyon aquifers extend for some unknown distance beneath the ocean, and this seaward extension presents two important problems: (1) the aquifers may crop out on the ocean floor, resulting in hydraulic continuity of the ground-water with sea water, and (2) the seaward extensions of these aquifers may act as ground-water storage reservoirs not inventoried in the hydrologic study.

The presence of two sharply defined submarine canyons a short distance south of the coastline indicates a reasonable possibility that the Oxnard aquifer crops out near the shore (pls. 3, 8). Among the lines of evidence suggesting that this aquifer is in contact with sea water in Hueneme Canyon are the following: (1) the development, during periods of low water levels, of a landward gradient in the piezometric surface near Port Hueneme, the contours having a roughly circular shape with the canyon as the center; (2) historic reports of fresh-water outflow in the Hueneme Canyon area at times of high water levels; (3) fluctuations of water levels in wells corresponding to, but lagging as much as three hours behind, tidal fluctuations; and (4) water-quality data indicating probable sea-water intrusion in 1951 near Port Hueneme. The principal evidence for a connection between the Oxnard aquifer and the ocean in the vicinity of Mugu Canyon is a response to tidal fluctuations in the wells.

It is estimated that the average thickness of the Oxnard aquifer offshore is about 100 feet, and that its specific yield is about 10 percent. The maximum area underlain by the offshore extension is estimated to be about 50,000 acres. These values lead to an estimated maximum possible offshore storage capacity of about 500,000 acre-feet of ground water. The physical characteristics and possible points of outcrop of the seaward extension of the Fox Canyon aquifer are uncertain, and therefore no discussion of its hydrologic characteristics is attempted here.

Ground-water in the semi-perched zone of the Oxnard Plain Basin is unconfined and contains water of poor quality. All aquifers that lie beneath the semi-perched zone contain confined ground-water.

When ground-water levels are high in the Oxnard Forebay Basin, as in 1944, water moves southwestward toward Hueneme and Mugu Canyons. When the water levels are sufficiently lowered by pumping in the Oxnard Plain and Oxnard Forebay Basins, no outflow to the ocean occurs, and further lowering may cause a landward movement of water in the seaward extension of the aquifer (pl. 8).

The Pleasant Valley Basin is second only to the Oxnard Plain Basin in irrigated acreage in Ventura County. Many aspects of the geology and ground-water hydrology of this basin are not clearly understood, owing to faulting, folding, rapid thinning of formations, multiple perforations of individual wells, and lack of adequate logging during drilling of wells. Aquifers in alluvium of Recent and late Pleistocene age are utilized in two areas of the Pleasant Valley Basin: between the Camarillo Hills and the Camarillo fault, and in the east and southeast parts of the basin south of the Camarillo fault. The aquifers in these areas do not appear to be connected with the Oxnard aquifer in the Oxnard Plain Basin (pl. 6).

The San Pedro formation underlies all of the Pleasant Valley Basin, and the most important aquifer in the basin is the Fox Canyon member of this formation. It is possible that the Fox Canyon aquifer is interconnected with the shallower sands and gravels in the eastern part of Pleasant Valley. The Santa Barbara formation beneath the Fox Canyon aquifer is reached by few water wells in the basin (pl. 6). Some wells obtain water from fractures in the volcanic rocks that are adjacent to and underlie the southern part of the basin, and from sedimentary strata interbedded with these volcanic rocks.

Structural features of the Pleasant Valley Basin include the Springville fault zone, the Camarillo fault, a major syncline and anticline between these faults, and the Camarillo Hills and Springville anticlines. These faults and folds appear to die out westward beneath the Oxnard Plain.

Ground-water in the Pleasant Valley Basin is generally confined, although the Fox Canyon member of the San Pedro formation is unconfined in a limited area near Somis, and some of the very shallow sands and gravels around the north and southeast sides of the basin may be unconfined, as well. The Pleasant Valley Basin appears to be replenished chiefly by subsurface inflow from East Las Posas Basin near Somis and from the Oxnard Plain Basin through the Fox Canyon aquifer. Replenishment of lesser magnitude appears to occur by subsurface inflow from the Santa Rosa Basin through the San Pedro formation, from the West Las Posas Basin through the Springville fault zone, and from the volcanic rocks south and southwest of the basin (pl. 6). Subsurface outflow toward the west may occur during periods of high water levels.

Change of ground-water storage in the Pleasant Valley Basin is considered to be negligible. Data are not sufficiently complete to permit an accurate estimate of total storage capacity of the basin, although it probably is of the same order of magnitude as that of the Oxnard Plain Basin.

Calleguas-Conejo Hydrologic Unit. The ground-water basins of the Calleguas-Conejo Hydrologic Unit (pl. 1) include the Simi, East and West Las Posas, Conejo, Tierra Rejada, and Santa Rosa Basins.

The Simi Basin is the only one of these that is essentially a simple alluvially filled type. The others are complex, and consist of two or more formations that are folded and faulted. Physical characteristics of this unit are summarized in table 3.

In the Simi Valley area permeable Quaternary alluvium is flanked and underlain by semi-permeable older formations. Folded strata of the Santa Barbara formation constitute a ground-water basin in the Tapo Canyon area, but these are separated from Simi Valley proper by less permeable older rocks.

Subsurface inflow enters the alluvial fill of the Simi Basin from adjacent older rocks, but no such inflow is known to enter from other basins. Ground-water in the alluvium moves westward except during dry periods when wells are heavily pumped, at which times the water table is depressed in the central part of the basin and the ground-water converges on this low area. The total storage capacity of the basin below the high-water level of 1929 is estimated to be about 180,000 acre-feet, and storage above this level is estimated to be about 40,000 acre-feet. In normal years, subsurface outflow leaves the Simi Basin on the west and enters the East Las Posas Basin. This flow has been estimated by the slope-area method to be about 100 acre-feet per year.

Studies by the Soil Conservation Service and the State Division of Water Resources indicate that the most suitable locations for major spreading works on the alluvium of Simi Valley lie near the mouth of Tapo Canyon, along Chivo Creek, and along Arroyo Simi just west of Santa Susana (pl. 4).

The principal water-bearing materials of the East Las Posas Basin are Recent and upper Pleistocene alluvium and the San Pedro and Santa Barbara formations (pl. 7). Semi-permeable Tertiary formations adjoin and underlie these water-bearing strata. The San Pedro

Table 3. Summary of selected characteristics of ground-water basins in Calleguas-Conejo Hydrologic Unit.

Basin	Area, in acres	Estimated weighted average specific yield,* in percent	Water-bearing formations	Principal aquifers	Estimated depth from ground surface to base of aquifers, in feet	Estimated thickness of aquifers, in feet	Condition of occurrence of ground-water	Estimated average yield of irrigation wells, in gallons per minute
Simi	10,760	8.6	Recent and Pleistocene alluvium	Lenses of permeable sediments	0-700	0-700	Mostly unconfined, some confined	400
			Older formations	Fracture zones and permeable lenses	0-400+	--	Essentially unconfined	100
East and West Las Posas	47,920	----	Recent and Pleistocene alluvium	Lenses of permeable sediments	0-200	0-200	Unconfined	400
			San Pedro formation	Epworth gravels	0-300	0-200	Essentially unconfined	300
				Fox Canyon member	0-2,000	200-400	Confined except near outcrop	600
			Santa Barbara formation	Grimes Canyon member	0-2,000	300-1,000	Confined except near outcrop	600
Conejo	28,930	5	Recent and Pleistocene alluvium	Lenses of permeable sediments	0-60	0-60	Unconfined	50
			Tertiary volcanic rocks and older sedimentary rocks	Fracture zones and permeable lenses in sedimentary rocks	1,000±	--	Essentially unconfined	50
Tierra Rejada	4,390	7	Tertiary volcanic rocks	Fracture zones	1,000+	--	Essentially unconfined	300
Santa Rosa	3,490	5	Recent and Pleistocene alluvium	Lenses of permeable sediments	0-200	0-200	Unconfined	600
			San Pedro formation	Fox Canyon member and other permeable lenses	0-700	0-700	Confined and unconfined	600
			Volcanic rocks	Fracture zones	1,500+	--	Confined and unconfined	600

* In zone of historic water-level change.

formation in this basin contains two notable aquifers, the Epworth gravels near the top of the formation, and the Fox Canyon member near its base. The Grimes Canyon member of the Santa Barbara formation is an aquifer that immediately underlies the Fox Canyon aquifer. In general, the East Las Posas Basin has a synclinal structure (pl. 7). This broad fold plunges gently westward, and includes several minor en-echelon synclines and anticlines. The San Pedro and older formations are folded and faulted, and only the alluvium is undisturbed.

Ground-water in the alluvial deposits of the East La Posas Basin is essentially unconfined, whereas ground-water in the Fox Canyon and Grimes Canyon members is confined by the overlying silts and clays except near the outcrop areas of these aquifers. In general, the ground-water in the various aquifers of the basin moves south, southwest, or west, and there appears to be movement into the Pleasant Valley Basin and, at times of high water levels, into the West Las Posas Basin. Subsurface inflow is limited to contributions from surrounding semi-permeable formations plus the approximately 100 acre-feet added annually from the Simi Basin. Total storage capacity of the aquifers in the East Las Posas Basin could not be estimated, but probably is very large.

Water could be spread artificially on any part of the outcrop area of the Fox Canyon or Grimes Canyon aquifers to reach the pumping zones (pl. 7). The most desirable spreading area appears to be in Happy Camp Canyon about 3 miles north of Arroyo Simi.

The West Las Posas Basin, like the East Las Posas Basin, has a synclinal structure. The principal aquifers are the Fox Canyon and Grimes Canyon members, which appear to be in contact in some places, but are separated by a clay bed of varying thickness in other places (pl. 6). This basin is replenished mainly by percolation of surface water in the outcrop area of the Fox Canyon aquifer. Some subsurface inflow from the East Las Posas Basin also may occur, and subsurface outflow leads into the Oxnard Plain and Pleasant Valley Basins through the Fox Canyon aquifer. Artificial spreading on the outcrop area of the Fox Canyon aquifer is physically possible, but the rugged topography limits areas in which effective spreading works could be constructed.

The Conejo Basin is essentially an upland valley area in which ground-water occurs in thin patches of alluvium, in fractures and weathered parts of volcanic rocks and Modelo shales, and in pervious zones of Modelo sandstones and strata of the Topanga formation. Most wells penetrate the alluvium completely and obtain water from underlying formations, as well. Some subsurface outflow is believed to occur from the Conejo Basin through the alluvial fill and fractured volcanic rocks into the Santa Rosa Basin, and some also may occur through volcanic rocks into the Pleasant Valley Basin.

The Tierra Rejada Basin is underlain principally by fractured volcanic rocks that comprise basaltic flows, agglomerates, and rhyolitic tuffs, and by conglomerates and clays that are interlayered with these rocks. The surface drainage divide is taken as the boundary of the basin, whose general structure is that of a westward plunging syncline. The basin is bounded on the north by the east-trending Simi fault, and on its west side is a north-trending fault that acts as a barrier to ground-water. A water-level differential of about 100 feet existed here in 1951, the level on the east side of the fault being higher.

No evaluation of storage capacity has been made for the Tierra Rejada Basin. No subsurface inflow is believed to occur into this basin, but limited subsurface outflow probably occurs westward into the Santa Rosa Basin.

In the Santa Rosa Basin, ground-water occurs in pervious zones of the alluvium and San Pedro formation, and in the fractured volcanic rocks. All of the rocks beneath the alluvium have been folded and faulted. The structural feature of greatest significance is the east-trending Santa Rosa syncline (pl. 7).

Subsurface inflow to the Santa Rosa Basin occurs from the Tierra Rejada and Conejo Basins. Inflow from both these sources is difficult to estimate because of the lack of well data and other information. Subsurface outflow through the San Pedro formation into Pleasant Valley has been estimated by the slope-area method to be about 200 acre-feet per year. Artificial spreading in the Santa Rosa Basin is feasible near the mouth of Conejo Creek, where most stream percolation has occurred.

Other Areas. The part of the northwestern Santa Monica Mountains that is drained southward to the ocean is termed the Malibu Hydrologic Unit (pl. 1). The principal water-bearing formations in this unit are Quaternary alluvium and Tertiary volcanic rocks, although some water is obtained from sedimentary strata of pre-Quaternary age. Alluvium and underlying volcanic rocks in the upper drainage areas of Triunfo and Medea Creeks yield some ground-water, but commonly in small quantities.

Ground-water occurs along the coast between the Ventura River and the Santa Barbara-Ventura county line, chiefly in alluvium-filled valley bottoms, beach deposits, and thin terrace deposits. These ground-water bodies are limited in size and sustain only a few wells.

The portion of the Cuyama River drainage area that lies in Ventura County (pl. 1) contains a few wells that draw from Quaternary alluvium apparently about 60 to 100 feet thick. In addition, the older Morales formation and parts of the Quatal formation, although not presently utilized by wells, appear from surface lithology to be potential reservoirs for ground-water. Rainfall in this area is low, and recharge to water-bearing formations probably is small.

Lockwood, Hungry, and Peace Valleys, in the upper part of the Piru Creek drainage (pl. 1), each contain a few water wells. Wells in Lockwood Valley appear to obtain water from Miocene continental sediments that lie beneath the alluvium, and wells in Hungry and Peace Valleys draw from Pliocene sediments of the Ridge Basin group, which also lie beneath the alluvium.

HYDROLOGIC INVESTIGATION

The hydrologic investigation in Ventura County (California Div. Water Resources, 1953) included a thorough study of underground water supplies with regard to quantity, quality, replenishment, and utilization, as well as the preparation of plans for development of local water resources to the maximum practicable extent. A comprehensive investigation of surface-water resources was included, as well. This involved collection, evaluation, and utilization of data on precipitation and stream flow. Previous records of ground-water levels in wells were studied, and a program of monthly and seasonal measurements in selected wells was carried on during the investigation (pl. 9). A continuous record of fluctuations in ground-water levels in the Santa Clara River Valley and the Oxnard Plain-Pleasant Valley area was available from about 25 water-stage recorders that have been maintained for many years, and these records were supplemented by 27 water-stage recorders that were placed on selected additional wells.

The nature and extent of present land use were determined, and estimates of future water requirements were made. Current irrigation practices in the county were studied in order to determine unit application of water to important crops on lands of various soil types, as well as the influence of climatic factors thereon. Studies were made of the quality of surface and ground waters, in order to evaluate their suitability for general and special uses, and to determine the causes of any poorness of quality.

The amount of water supply in the form of precipitation, surface streamflow, and subsurface flow was determined for each of the major hydrologic units within the county, in part by the application of geologic study to subsurface flow. Similarly, surface and subsurface outflow and present water requirements were computed. The studies also included determination of presently developed safe yield of surface and ground-water supplies (pl. 10), present and probable future supplemental water requirements, present waste to the ocean of surface and ground waters, and the portion of this waste susceptible to conservation in surface and underground reservoirs.

The development of plans for possible additional conservation of local water supplies included field examination of feasible dam sites and preparation of preliminary cost estimates for structures at many of these sites. Preliminary plans and estimates of cost also were prepared for works that would furnish supplemental water from the proposed southern California Diversion conduit of the Feather River Project, and from the Colorado River supply of the Metropolitan Water District of southern California.

SUMMARY OF CONCLUSIONS

A full summary of the conclusions reached after completion of the Ventura County Investigation appears in Bulletin No. 12 of the State Water Resources Board (California Div. of Water Resources, 1953, pp. 5-1 to 5-9), and the conclusions of principal general interest can be summarized as follows:

1. Problems of water resources in Ventura County are manifested in the consistent lowering of ground-water levels, sea-water intrusion to pumped aquifers, degradation of ground-water quality, and serious general diminution of surface- and ground-water supplies during periods of drought.

2. Partial solution of these problems will involve further regulation of the erratic local water supplies, so that waste conserved during wet periods can be made available for beneficial use during periods of drought. Final solution of the problems will involve the importation of water from sources outside the County.

3. The present main sources of water supply in the County are direct precipitation and runoff from tributary drainage areas. Imported water at present constitutes a minor item of supply. Mean annual precipitation ranges from a minimum of about 12 inches near the coast to a maximum of about 32 inches in the northerly mountainous areas. Mean annual runoff to the ocean from the Ventura and Santa Clara Rivers, with the present pattern of land use and water-supply development, is about 230,000 acre-feet.

4. Regulation and re-regulation of the water supplies is now accomplished almost entirely through storage in ground-water reservoirs. A total of 17 major ground-water basins have been identified in the County, 16 of which are currently of economic importance. The safe yield of the presently developed water supply is about 107,000 acre-feet per season, distributed as follows: Ventura Hydrologic Unit, 9,400 acre-feet; Santa Clara River Hydrologic Unit, 73,200 acre-feet; Calleguas-Conejo Hydrologic Unit, 23,700 acre-feet; and Malibu Hydrologic Unit, 800 acre-feet.

5. Piezometric levels in confined aquifers of the Mound, Oxnard Plain, and Pleasant Valley Basins were drawn below sea level during the drought period 1944-1951, and landward gradients from the ocean prevailed in these aquifers. During 1951, sea water invaded a part of the Oxnard aquifer that was being actively pumped in the Oxnard Plain Basin.

6. Surface- and ground-water supplies of Ventura County generally are of good mineral quality, and are suitable for irrigation and other beneficial purposes.

7. The gross area that presently requires water service in the County amounts to about 140,000 acres, distributed as follows: Ventura Hydrologic Unit, 12,000 acres; Santa Clara River Hydrologic Unit, 103,000 acres; Calleguas-Conejo Hydrologic Unit, 25,000 acres; and Malibu Hydrologic Unit, 500 acres. About 235,000 acres in the County are considered susceptible to concentrated and intensive water-using developments.

8. The present mean annual water requirement of the County is about 180,000 acre-feeet, distributed as follows: Ventura Hydrologic Unit, 13,000 acre-feet; Santa Clara River Hydrologic Unit, 133,000 acre-feet; Calleguas-Conejo Hydrologic Unit, 33,000 acre-feet; and Malibu Hydrologic Unit, 1,000 acre-feet.

9. The probable ultimate water requirement of Ventura County will be about 389,000 acre-feet, distributed as follows: Ventura Hydrologic Unit, 39,000 acre-feet; Santa Clara River Hydrologic Unit, 227,000 acre-feet; Calleguas-Conejo Hydrologic Unit, 104,000 acre-feet; Malibu Hydrologic Unit, 14,000 acre-feet; and remainder of the County, 5,000 acre-feet.

10. The present mean annual requirement for supplemental water in the County is about 73,000 acre-feet, distributed as follows: Ventura Hydrologic Unit, 4,000 acre-feet; Santa Clara River Hydrologic Unit, 60,000 acre-feet; and Calleguas-Conejo Hydrologic Unit, 9,000 acre-feet. Supplemental water is now required in the Ventura Hydrologic Unit in order to eliminate ground-water overdraft in the Ojai and Upper Ventura River Basins, and to stabilize the currently erratic and deficient surface-water supplies. Supplemental water is now required in the Santa Clara River Hydrologic Unit in order to prevent intrusion of sea water into pumped aquifers of the Oxnard Plain and Pleasant Valley Basins. There is no present requirement for supplemental water in the Piru, Fillmore, and Santa Paula Subunits of the Santa Clara River Hydrologic Unit, but supplemental water is now required in the Calleguas-Conejo Hydrologic Unit in order to prevent progressive lowering of ground-water levels, with attendant lowering of ground-water quality, in the Simi, East and West Las Posas, and Tierra Rejada Basins.

11. Under forecast ultimate conditions of development in the County, the mean annual requirement for supplemental water will be about 266,000 acre-feet, distributed as follows: Ventura Hydrologic Unit, 30,000 acre-feet; Santa Clara River Hydrologic Unit, 142,000 acre-feet; Calleguas-Conejo Hydrologic Unit, 81,000 acre-feet; and Malibu Hydrologic Unit, 13,000 acre-feet.

12. An immediate source of supplemental water is available locally to Ventura County in the form of surface waters presently wasting to the ocean. The salvage of these waters will require the development of equalizing storage capacity, either in surface reservoirs or in now undeveloped ground-water storage capacity. Supplemental water could be made available to the County in the form of imports from the Colorado River, through facilities of the Metropolitan Water District of southern California. A future source of supplemental water, sufficient in quantity to satisfy those probable ultimate water requirements of the County in excess of the yield from feasible developments of local water supply, will be made available by means of the Feather River Project.

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GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER VII

MINERALOGY AND PETROLOGY

1954

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Ferry Building, San Francisco 11
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San Francisco
Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER VII

MINERALOGY AND PETROLOGY

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Editorial Note:

CHAPTER SEVEN presents a sampling of information and thought concerning minerals, igneous rocks, and metamorphic rocks in southern California. This is a region that is world-famous for some of its mineral occurrences, including the contact-metamorphic assemblage at Crestmore, the pegmatite deposits at Pala, Mesa Grande, and other localities in the Peninsular Range province, the saline deposits of the Mojave Desert and Basin-Range provinces, and the recently discovered concentrations of rare-earth minerals in northeastern San Bernardino County. Also exposed for study are the great composite batholiths of the Sierra Nevada and the Peninsular Ranges, complex sequences of Mesozoic and Cenozoic volcanic rocks, and broad terranes of highly varied metamorphic rocks.

The eight papers in this chapter place emphasis upon description and discussion of outstanding examples of rock and mineral assemblages, rather than merely upon a cataloguing of occurrences by type or by geographic position. An attempt also has been made to point out and to examine critically some of the major problems of structure, composition, sequence, and origin that remain to be fully solved.

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1. MINERALS IN SOUTHERN CALIFORNIA

By Joseph Murdoch * and Robert W. Webb †

Introduction. We in California take pride in the fact that in the State have been found occurrences of more than 535 well-defined mineral species, and a record list of first discoveries of new species. World-famous mineral localities include the contact metamorphic assemblage at Crestmore, Riverside County; the gem pegmatites of San Diego County; and the salines and borates of Searles Lake and Death Valley. Between 1857 and 1938, 56 new minerals were discovered, of which 23 have not yet been found elsewhere. Southern California can claim the lion's share of new mineral discoveries with 16, as compared with 7 for the rest of the State.

For a complete list of California minerals and their occurrences, the reader is referred to Bulletin 136 of the California Division of Mines, which, with its supplement,‡ provides a detailed record through December 1951. In this sketch only the most important and interesting occurrences are presented, particularly those in which reasonably good collecting or observation may still be possible. The accompanying key map (fig. 1) shows the approximate location of the localities that are discussed.

Minerals and Their Early Use in Southern California. Since prehistoric times, California has been a producer of minerals beginning, so far as is known, with the working of turquoise deposits in San Bernardino County. There is some evidence that other minerals were used by the Indians as charms (quartz crystals), war paint (cinnabar), or as arrowheads (flint as well as obsidian). But of course the outstanding event in California history was the discovery of gold at Sutter's Mill in 1848. There were earlier discoveries in southern California at Placerita Canyon, at points near Yuma, and elsewhere; but these touched off no such overwhelming excitement as did the find at Sutter's. The gold deposits first worked were in the form of placers, and numerous large nuggets were found. Subsequently the Mother Lode quartz veins were discovered and developed, and some of the mines of those early days are still producing. The record mass of gold weighed 2340 ounces, and was called a nugget, although it was really a detached mass of gold quartz; other very large masses were true nuggets.

The fabulous richness of California gold placers was in part the result of the geological history of the Sierra Nevada. Original gold-bearing quartz veins were deposited in Jurassic and earlier rocks, after the early uplift of the Sierra during the intrusion of the dominantly silicic complex known as the Sierra Nevada batholith. The uplifted range was then reduced to a surface of mature relief, with accumulation of gold—derived from upper, eroded portions of the veins—as placer deposits in stream valleys. Later movements produced uptilting of the Sierran block and the formation of the present day Sierra, resulting in rejuvenation of streams flowing over the westward tilted surface, with attendant reconcentration and enrichment of placers in new valleys. Some of the old stream valleys were buried by lava flows before this uplift.

Since early pioneer times, California has been a land famous for its minerals. None of the minerals has been as glamorous as the gold which was originally sought and found in such vast quantity; nevertheless many have been, and still are, of great commercial value, and many others have provided scientists with stimulating problems in mineralogy. Some have also been helpful in unravelling geologic problems, as witness the characteristic crossite and other minerals of the San Onofre breccia beds, which have made possible positive identification of the source of these sediments.

Deposits of turquoise in the northeastern part of San Bernardino County were worked by prehistoric Indians. The occurrence was rediscovered in 1897 by T. C. Bassett, who found the ancient workings, some of which yielded a number of primitive stone hammers, thus the name: Stone Hammer mine. The following year the San Francisco Call financed an expedition, headed by Dr. Gustav Eisen, of the California Academy of Sciences, to explore the mine. His account was published in an extensive article in the Call of March 18, 1898, and led to considerable prospecting. Dr. Frederick Kunz in 1905 wrote a good description of the find and of the general character of the area. The rocks of the region consist largely of basalt flows from a series of extinct craters. Smaller areas of decomposed sandstone and porphyry, with harder quartzite and schist, contain veinlets and nodules of turquoise. Turquoise also occurs as fragments in disintegrated quartz rock. The mode of occurrence appears to resemble closely that at Turquoise Mountain, Arizona. Stone tools are abundant in the old workings, which are seen as shallow saucer-like pits in the canyons and on the slopes of the hills. Abundant rock carvings are found throughout the whole region, some identifiable as "Aztec Water Signs," but others as yet uninterpreted. It is suggested that these workings may have been abandoned as long as a thousand years ago.

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‡ No references are cited in this article. The material is largely summarized from *Minerals of California*, California Division of Mines, Bulletin 136, 1948; and Supplement, 1952; by the writers of this article. In these sources exhaustive references are given. Acknowledgment is hereby made of indebtedness to the many geologists whose work has made the information in this paper available.

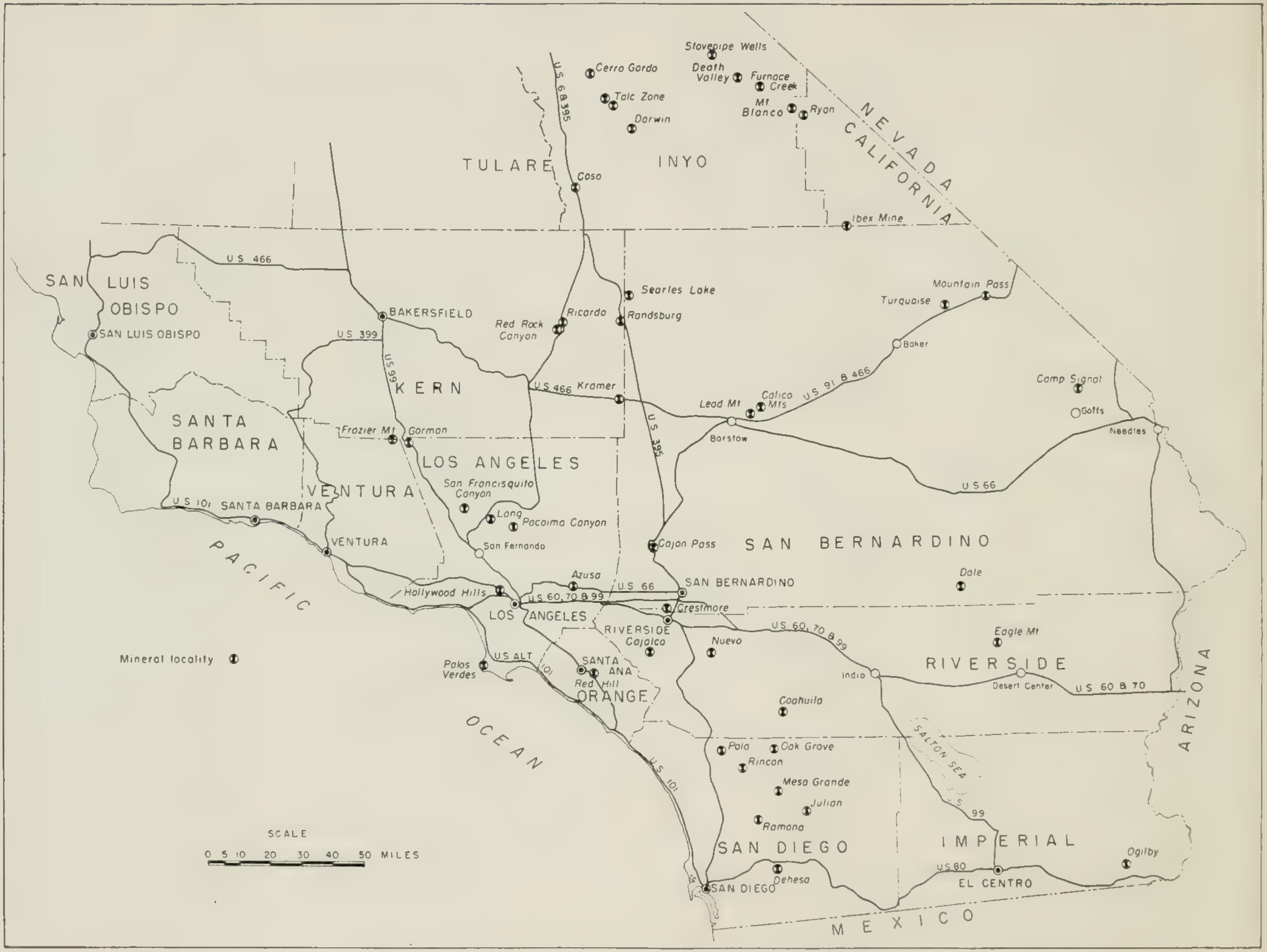

FIGURE 1. Key map to mineral localities in southern California.

California Borates. A few years after the discovery of gold, Dr. John A. Veatch detected boron in some of the spring waters of central California, and found crystals of borax in the muds of Borax Lake in Lake County. This discovery led to extensive prospecting, with the result that small deposits were found in the incrustations of Searles Lake in 1862. The deposits in Death Valley, made famous by the twenty-mule team trains, were discovered in 1873.

It is interesting to trace the development of the borax industry from beginnings in the playas of Death Valley to the modern mining operations in the Kramer district and Searles Lake. For some years the production of borax was a primitive process of scraping up efflorescences of borax and ulexite from the playa surfaces at several points on the floor of Death Valley. The ore thus produced was treated at the Old Harmony borax works, Ashford's mill, and other places, and the product was shipped to Mojave. Transportation was by wagon trains, each carrying along its own water wagon for the ten-day journey; one of these outfits, with its huge broad-tired wheels, can be seen today at the entrance to Furnace Creek Ranch.

In 1882 a new boron mineral, colemanite, was discovered in large quantities in the uplifted and tilted Tertiary volcanics and lake beds of the Mt. Blanco and Ryan districts on the eastern edge of Death Valley. This source was so rich that the playa workings were rapidly abandoned. Following this early discovery, deposits of colemanite were found and developed in the Lockwood Valley region near Frazier Mountain (1898); at the Sterling Borax mine, in Tick Canyon near Lang (1909); and in the Kramer district (1913). This last discovery was made by a Los Angeles physician drilling for water to supply a sanitarium. Further exploration in this area resulted first in the discovery of a very large body of nearly pure borax (the old Suckow mine) at a depth of about 150 feet below the surface, and later (about 1927) of a still more extensive body of a new mineral, kernite (sometimes locally called rasorite). Kernite is the only known ore from which more than 100 percent recovery can be made, as the pure mineral carrying four molecules of water of crystallization is soluble in water, and recrystallizes as borax, picking up in the process six additional molecules of water, an increase of nearly 20 percent in weight.

In the borax of the Suckow mine, ulexite in small amount occurs as cross-fiber veins, and as curious mushroom or fungus-shaped radiating aggregates of fibers which in part at least are pseudomorphs after probertite, another mineral that occurs only in California. The kernite deposit is thought probably to have been formed by the fusion of an original borax deposit and its recrystallization in the absence of any excess of water. Kernite is one of the minerals discovered in California and, to date, not found elsewhere.

Colemanite is never found in playas, and is relatively insoluble in water; so it is considered that deposits of this mineral have been formed by a reworking of original borax-ulexite playas, like those existing at the present time on the floor of Death Valley. As a result of this reworking, in most cases perhaps after uplift and tilting of the playa beds, sodium has been largely or wholly removed, and the boron combined with calcium from lime-rich layers of sediments or from limestones, to form colemanite. Colemanite occurs as geodal nodules, irregular or rounded masses of radiating prisms, as irregular veins, or as disseminated replacements of limestone or shale. Locally, as in 20 Mule Team and Corkscrew Canyons in the Mount Blanco district of Death Valley, colemanite has in part undergone a series of alterations, resulting in the formation of the rare minerals inyoite and meyerhofferite. Inyoite, with more water than colemanite, may have been formed by the hydration of the latter. Meyerhofferite occurs in part as masses of needlelike crystals pseudomorphous after inyoite, but also, and more abundantly, as reticular aggregates of slender prismatic crystals. Meyerhofferite may represent a stage of dehydration from inyoite. Meyerhofferite has thus far been found only in California. A second generation of colemanite, usually in small, simple crystals, follows and accompanies the formation of meyerhofferite.

Another rare calcium borate, priceite (pandermite), is plentiful in the same Mt. Blanco area, as veins and nodules in shale and basalt. Priceite is accompanied by coarsely crystalline colemanite and finely compact howlite (a borosilicate of calcium) in nodules or irregular veins.

Howlite occurs sparingly as white, powdery masses accompanying colemanite in deposits in the Calico Mountains, and abundantly as solid, cauliflower-like growths in Tick Canyon and Lockwood Valley. In the Tick Canyon deposit, several borates are present in addition to colemanite and howlite. Flattened aggregates of irregularly radiating prisms, mainly probertite, $NaCaB_5O_9 \cdot 5H_2O$, are abundant on some of the dumps. These aggregates are thought to have been originally "cotton ball" ulexite, such as is found in playas, squeezed and flattened in the compression and tilting of the layers (now nearly vertical at Tick Canyon) of a playa deposit. Probertite may be supposed, then, to have been formed by dehydration of original ulexite. A reversal of this change also must have occurred, as many probertite nodules are seen to be altered again wholly or in part to ulexite. At Tick Canyon an additional new borate mineral has been found: veatchite, a strontium borate. It occurs in thin silvery plates on fracture surfaces of gray shale, as massive nodular aggregates of platy grains, and, in one specimen, as poorly formed crystals developed in cavities in a colemanite vein.

Gem Tourmaline Deposits. In southern areas of California, largely in San Diego County, are extensive occurrences of lithium-bearing pegmatites, in which tourmaline of gem quality, transparent and colored pink, red, green or blue, is found. With these varieties of tourmaline are other gem minerals: beryl, either golden or pink (morganite); topaz; the clear lavender variety of spodumene known as kunzite; and, in a few deposits, cinnamon garnet. The pegmatites form tabular and irregularly bulging dikes cutting the igneous and metamorphic country rock, and strike regionally nearly north and south over large areas. The most famous and largest deposits are those at Pala and Mesa Grande, and numerous others of lesser account are near Ramona, Coahuilla (in Riverside County), and Oak Grove. These and other pegmatite occurrences are described elsewhere in this chapter (Jahns, Contribution 5).

Productive mining in these pegmatites has been at a standstill for many years, although recent vigorous collecting by mineralogists and others has continued. A new find of kunzite in the Ashley mine (the old Vanderburg-White Queen) at Pala, has yielded a considerable number of wonderfully fine specimens of gem quality, and others of great mineralogical interest. A recent study of the lithia pegmatite region by R. H. Jahns and L. A. Wright has resulted in the finding of a number of mineral species new to California, although not new minerals. These include phenakite, bertrandite, stibiotantalite, and zinnwaldite. Also noted by them at Pala were helvite and petalite, which had been reported earlier from the Rincon district.

The gem pegmatites were discovered in 1872 on the southeast slope of Thomas Mountain, in Riverside County, by Mr. Henry Hamilton. The initial find was kept secret for several years, and was not recorded until later in reports of the California State Mineralogist. Kunz confirmed the earlier date of discovery from his personal record, and said that he had in his possession a fine specimen from the Riverside County locality, obtained prior to 1873. The next big discovery, at Pala, was announced in 1893. From this locality came the famous massive lepidolite shot through with needles of clear pink tourmaline (rubellite), specimens of which are in nearly every museum collection in the world. In 1898 gem tourmaline was found in abundance at Mesa Grande. Then in 1902 more new finds at Pala, near the original location, produced large and beautifully colored crystals of tourmaline as well as kunzite, the new, lilac-colored gem variety of spodumene. The kunzite was first found on Hiriart Mountain, just east of Pala, and in the following year it also appeared in the mineral suite of the Pala Chief mine.

In the Stewart mine, large masses of solid amblygonite were found, associated with metallic bismuth, various rare bismuth carbonates, as well as with secondary calcium phosphates of the apatite group, the rare mineral jezekite, and some others as yet unidentified. In the same deposit, lithiophilite occurred in crude crystals, usually altered, or altering, to a complex series of secondary products. This alteration shows the same sequence as that first recorded in the famous Varuträsk pegmatite in Sweden; in some of the New Hampshire pegmatites (as at Palermo); and in some of the beryl-tantalite pegmatites of northeastern Brazil. The alteration results from progressive oxidation first of the iron, and then of the manganese, in the original mineral, to produce sicklerite (described and named by W. T. Schaller from Pala), then purpurite. If more iron than manganese is present, the series is ferri-sicklerite to heterosite. Further oxidation and hydration result in the formation of a number of rare minerals like huréaulite and meta-strengite, stewartite, salmonsite, probably some members of the rockbridgeite group, and finally, manganese oxides.

The other gem-bearing pegmatites of the region have been extensively prospected and have yielded some good gem material, but in general not in any great amount. Tourmaline, topaz, beryl, and gem garnet are in the list, with local rare cassiterite.

A dike opened about 1906, near Rincon, is noteworthy for the presence of a considerable amount of common spodumene in tabular crystals as much as six inches in length. This mineral is embedded in, and partly replaced by, massive prismatic petalite, found in the United States in only one or two other localities. Associated with these two minerals are rare, minute yellow crystals of helvite (also found later at Pala).

Contact Metamorphic Minerals of Crestmore. Less spectacular, but of perhaps greater scientific interest, is the great contact metamorphic deposit at Crestmore, in Riverside County. Here is assembled almost the greatest number of minerals ever recorded from a single occurrence, perhaps topped only by Franklin, New Jersey, and Langban in Sweden. The total number of known species to date stands at 119, and in addition a dozen or so probable new species have been observed, but not as yet verified. The great variety is apparently due to a very favorable set of conditions which have led to formation of many unusual compounds, as well as those of the normal contact metamorphic assemblage (see Burnham, Contribution 7, this chapter). The deposit occurs in a roof pendant of crystalline limestone (locally magnesian) surrounded by silicic igneous rocks (possibly parts of the southern California batholith), and cut by small masses of pegmatite and pegmatitic rocks. The most obvious and primary effect has been a recrystallizing of the limestone into a coarse-grained calcite, accompanied by the production of an unusual sky-blue color in most of it. Recrystallization of impurities in the limestone, plus addition of material from the intrusives, plus recombination of all these with the calcite of the limestone, has resulted in formation of the usual contact minerals garnet, epidote, wollastonite, diopside, and idocrase. Some of the zones, especially close to the contacts, are completely silicated, and form a compact aggregate, usually of garnet, diopside, and idocrase with some spinel. In some massive zones, the common minerals are accompanied by spurrite, gehlenite, monticellite, and plazolite, which often are recognizable only in thin section. As a rule the textural relationships here are complex and unusual, in places producing the effect of graphic intergrowths. In other places, generally farther away from the intrusives, replacement of limestone has not been complete, and the result is crystalline calcite peppered more or less thickly with rounded grains or reasonably perfect crystals of idocrase, diopside, some gray monticellite, and locally what was originally wilkeite now altered to white fibrous crestmoreite. Here also have been found minute honey-yellow octahedra of perovskite.

In addition to the more ordinary minerals, reactions with later-stage solutions have formed a series of hydrothermal minerals of unusual character. Many of them are hydrated lime silicates, others are more complex compounds. In this group appear rare minerals like thaumasite, in thin veins of slender prismatic crystals; crestmoreite and/or riversideite (there is some doubt as to any difference between these two), appearing as veins in the interstices of idocrase crystals and as pod-like masses disseminated in calcite, in the form of white fibrous material altered from original wilkeite (as shown by occasional residual cores) or other earlier minerals; jurupaite; tilleyite; okenite; and others.

In pegmatite contact zones are found the usual garnet-epidote rock and occasionally borates of the ludwigite type; some other unknown magnesium borates or borosilicates in prismatic growths, and their alteration products; and the usual abundant wollastonite. In the pegmatites themselves appear occasional and inconspicuous zircon, sphene, late-phase zeolites, and prehnite. Rare allanite (var. treanorite) is found along with iron-rich almandite garnet, and an altered thorium silicate occurs in one of the larger pegmatites.

The magnesium-rich layers or zones in the limestone are marked by the abundant development of roughly octahedral grains of brucite, in foliated aggregates. These are pseudomorphs after periclase, as shown by the discovery of some unaltered cores of this mineral. These are usually of microscopic size, but some have been found large enough to see with the naked eye. Also present in the magnesium limestones, along fractures of the rock, is hydromagnesite in flattened radiating clusters of blades, or less commonly, in well-formed crystals.

A recent discovery has been made of a strongly silicated portion of the contact zone made up primarily of fine, sugary white garnet, with minor intergrown wollastonite and diopside, and containing large lenticular masses of nearly pure massive brown monticellite and rare irregular patches of blue crystalline calcite. This entire zone is cut by fractures, in some places showing slickensides. These fractures are filled with a variety of minerals, among which thaumasite is not uncommon. Other crack walls and slickenside surfaces are coated with foshagite, in long white fibers, and still others are coated with a white hydrous calcium silicate-carbonate, thus far unnamed, in gossamer-thin flaky crystals or aggregates of such flakes. These are commonly accompanied by a bright blue mineral, also flaky when individuals develop, but more commonly occurring as a thin coating over the surface, or mixed like paint with the white material. This is somewhat similar to the white mineral in composition but contains also a little copper, and has a different structure (as shown by X-ray powder photographs).

Locally, and often near or in the calcite patches, are small rounded or irregular blebs of sulphides: galena, bornite, chalcopyrite, with all three sometimes intergrown in the same bleb. The galena is in part altered to cerussite, locally occurring with various lead or lead-calcium silicates. Of these, minute blue-green or yellow prismatic crystals and crystalline crusts have been identified probably as nasonite, known previously in this country only from Franklin, New Jersey. Another, a calcium-lead silicate as yet unnamed, occurs in minute clusters or balls of colorless platy crystals which are probably monoclinic. Still other lead silicates appear as finely fibrous, or as chalky, powdery coatings.

A new find of great interest has recently been made on cracking open one of the boulders on the so-called 910-foot level of the Commercial quarry. This boulder apparently was fairly massive diopside-calcite-monticellite-brucite rock which broke along an irregular fissure lined with crystals, mainly of calcite, but locally with clusters and bundles of tabular crystals of scawtite, a rare carbonate-silicate of calcium, first found at Scawt Hill, Antrim, by Tilley, and later noted in microscopic study in thin-sections from a deposit near Neihart, Montana. The Crestmore occurrence exactly parallels that at Scawt Hill, and has supplied crystals good enough to measure on the goniometer, and by X-ray methods. The rare mineral afwillite, occurring in the same matrix, as massive veins and as radiating clusters of slender prismatic crystals was identified by Drs. Switzer and Bailey about 1950. The mineral was observed and identified independently by Murdock in the Fall of 1952.

In spite of the fact that collecting has been going on at Crestmore for years, and in general no new quarry faces have been available for hunting, a good number of the rare minerals of this locality still can be found by industrious searching in the old Commercial quarry workings. New finds also can still be made even now, as shown by the recent discoveries of perovskite and scawtite.

In the nearby Jensen quarry, developed in a somewhat similar contact metamorphic deposit, a number of interesting minerals have been found, including geikielite, chondrodite, spinel in pinkish crystals as much as a quarter of an inch across, phlogopite, and, in veins through the contact zone, a number of metallic sulphides: arsenopyrite, sphalerite, pyrrhotite, and gersdorffite. There are perhaps sixty-odd species in all, but Jensen does not approach Crestmore in mineral richness.

Occurrences of Mineral in Amygdaloids. Zeolites of various species are rather abundant in Tertiary amygdaloidal basalts at several localities in the southern part of the State. The most widely known of these is the Red Rock Canyon area, where there is an extensive series of ash beds and tuffs and a few interstratified lavas, some of which are highly vesicular. In some of the vesicular horizons, the cavities are filled with abundant natrolite in clusters or massive aggregates of slender prismatic crystals, usually accompanied by clear glassy analcime, massive and in well-developed trapezohedrons. Locally flesh-colored to nearly colorless phillipsite is found in rather poor prismatic crystals and also in massive amygdule fillings. These minerals are often accompanied by minor amounts of calcite, quartz, and chalcedony, and by considerable common opal, much of which has been rendered crumbly by dehydration. Some cavities are lined with crusts of green, fine-grained or fibrous minerals, perhaps corundolphilite or celadonite or nontronite. In the adjacent basalt occur flaky or platy red-brown grains of iddingsite. Other zeolites such as thomsonite have been reported from here, but are rare. Similar analcime-natrolite amygdules are abundant in one of the lava flows close to the Sterling Borax mine in Tick Canyon.

A greater variety of zeolites and associated minerals has been observed in the shattered and amygdaloidal basalts of the Santa Monica Mountains west of Cahuenga Pass. Here are extensive fracture coatings and cavity fillings of analcime, natrolite, ptilolite, laumontite, and stilbite, with platy crystals of apophyllite and drusy coatings of prehnite. These are well shown in the Pacific Electric quarries in the basalt of Brush Canyon.

Near Coso Hot Springs an obsidian flow carries unusually large and showy lithophysae, ranging in size from a quarter of an inch in diameter up to 2 or more inches. Many of the largest have been caved in by pressure of the still viscous lava, producing a curious geometric fracture pattern in the filling, but most are unbroken, and usually nearly spherical. The filling is a porous mass of radiating slender rod-shaped orthoclase, associated with spherulitic aggregates of fine-grained cristobalite or hedge-like clusters of tiny tridymite plates. A pattern of concentric layering is imposed on the radial structure, and shrinkage spaces formed parallel to this have their surfaces abundantly dotted with additional beads of cristobalite and tridymite. Fayalite, in thin platy crystals, dark-brown in color, occurs implanted on these shrinkage surfaces, and in general appears to have been the latest mineral to form.

Rare-Earth Minerals. Several occurrences of rare-earth minerals are known in California. One of the most interesting of these is in the Southern Pacific Silica quarry at Nuevo. Here, a pipe- or stock-like pegmatite has a crudely zoned structure, composed of quartz and abundant pinkish feldspar, thin sword-like blades of biotite as much as 3 feet long, and large black tourmaline crystals, separated or in rosette patterns, forming a general margin around a quartz-rich core. All the minerals are considerably shattered and show a strongly developed sheet structure. Few uncracked fragments of quartz can be found more than half an inch thick and more than an inch in the other dimensions. The quartz is usually white, with occasional smoky areas and some fairly extensive patches of rose color. Some of this quartz, particularly the rose variety, shows asterism, and on this account is popular with collectors.

The rare-earth minerals occur mostly in the feldspar-rich zone, along platy fracture surfaces, although some also occur in the quartz mass. The most abundant of them is monazite, which appears in tabular grains and well-developed crystals, amber in color, usually very small, although some individuals as large as an inch across have been collected. Often associated with it is cyrtolite, which usually appears in radiating, partly flattened clusters of minute crystals of square prisms capped by a simple pyramid. In color the cyrtolite varies from creamy or grayish white to dark green, and generally it is quite opaque. Color variation is apparently due to differences in secondary alteration. Not uncommonly the cyrtolite is in parallel growth with flat pyramidal xenotime, in intergrowths sometimes very distinct and well-formed, but deteriorating in perfection to the point where the group is merely a nodule with a bare suggestion of crystal pattern, or not even any indication of crystal form for either mineral. Samarskite, in crude crystals or small irregular masses, has been found here very occasionally, and columbite, though present, is even less common.

The most important rare-earth deposits in the United States are the newly found bastnaesite occurrences near Mountain Pass, in northern San Bernardino County, where large bodies of commercial-grade rock have been uncovered. The rare-earth minerals occur in veins in and near contact zones of alkali syenite or shonkinite, as well as in intrusive masses of carbonatite. The principal rare-earth mineral is bastnaesite, which in places makes up ten or more percent of the ore mass. The bastnaesite is pinkish or flesh-colored, in irregular grains and masses, with a near-greasy luster. It is associated with much barite, and with minor amounts of monazite, a little parisite, and other unidentified cerium carbonates (see also Olson and Pray, Contribution 3, Chapter VIII).

Salines of Searles Lake. One of the world's mineralogically richest saline deposits is at Searles Lake, in San Bernardino County, where at least 27 mineral species have been recorded. Searles Lake basin is one of a series of lake basins which were large inland freshwater lakes. During the Pleistocene glacial epoch, overflow occurred progressively from northerly to southerly and easterly basins into Searles Lake (see Blackwelder, Contribution 5, Chapter V). Searles Lake basin is one of the lower of the sequence, probably draining during a part of the Pleistocene into the Panamint basin and thence into the Death Valley basin. Northerly basins included Owens Lake, which overflowed into Indian Wells (China Lake) Valley, which in turn spilled into Searles Lake. Searles was the recipient of concentrated waters from a series of basins up-drainage, and consequently became an accumulation point for much of the mineral matter originally dissolved in a very great volume of water. With the lowering of the water level below the spillway rim, continued evaporation resulted in the deposition of a large and thick body of salts, still not perfectly solid, but instead saturated by interstitial mother liquor in which the more soluble compounds have remained. This liquid, continually replenished by seeping of surface water from the surrounding country, is the source of the numerous elements, of which potassium is commercially the most important, which are being recovered by chemical processes at the present time (see Mumford, Contribution 2, Chapter VIII).

The minerals of the area have been identified in the surface crusts on the lake bed and in drill cores recovered during exploration of the area. Some borax and ulexite were found in surface deposits. The rare minerals burkeite, hanksite, nahcolite, northupite, schairerite, searlesite, sulphohalite, and tychite have apparently been formed in the subsurface layers of the halite mass by reaction of the mother liquors with the surrounding halite, trona, glauberite, and other minerals of the original playa deposits. Some of these minerals have been found in other deposits, but tychite and burkeite have not been recorded elsewhere in the world. Hanksite has recently been found also in saline evaporation crusts on the shores of Mono Lake.

Cerro Gordo District. The Cerro Gordo mine, on the crest of the Inyo Mountains near their southern end, was an extensive producer of silver and lead in the late sixties and early seventies of the last century. With exhaustion of the bonanza ores, mining lapsed until the discovery of zinc carbonate ores in 1911, when mining was revived. In the early days the bullion from the mine was carried across Owens Lake (now virtually dry) on a small steamer! The common minerals were galena carrying silver, and cerussite and smithsonite. Locally tetrahedrite and pyrite were prominent. The unusual minerals of the district, which often yielded spectacular specimens, were formed in the oxidized zones of the ore. The showy and bright-colored minerals were linarite, azurite, malachite, and caledonite. Other rare minerals, in general less conspicuous, include atacamite, aurichalcite, bindheimite, hydrozincite, leadhillite, mimetite, and possibly liroconite and plumbogummite. Other mines nearby in the district add to this list tetradymite, bournonite, dufrenoysite, stromeyerite, jamesonite, and possibly greenockite. The ores occur in Upper Paleozoic limestones as replacement and contact metamorphic deposits. The nearby Darwin district has produced ores with similar unusual mineralogy.

Other Unusual Occurrences. The old-time Calico district near Barstow, in San Bernardino County, was noted for its oxidized silver ores, particularly cerargyrite with some bromyrite, and iodyrite, in small but very rich deposits. Practically all remaining representatives of these minerals are now in the hands of collectors.

In the same Calico Mountains is one of the formerly important borate deposits, mainly of colemanite, with a little accompanying howlite and priceite. Nodular masses in cherty limestone layers form geodes containing strontianite as drusy coatings, with occasional water-clear crystals of celestite, some of them beautifully formed.

At Red Mountain, south of Randsburg, the California Rand silver mine produced a considerable amount of silver chloride ore, and at greater depth, sulfide ore in which the principal mineral was the relatively rare miargyrite, with very minor amounts of proustite and pyrargyrite. Some of the miargyrite is beautifully crystallized, showing complex development of forms. The unusual mineral pyrostilpnite has been found here.

Dumortierite occurs as an important constituent of a pegmatite dike near Dehesa, in San Diego County. The mineral appears in lilac-colored prisms, usually forming plume-like aggregates. In part it is altered to pseudomorphs of muscovite. The mineral is also found near Ogilby, in Imperial County, and is associated with black tourmaline in seams of granite in Temescal Canyon, near Corona, Riverside County.

Pyrrhotite in norite (probably a magmatic segregation), near Julian in San Diego County, is of particular interest because of the presence in the ore of small amounts of violarite and pentlandite, identifiable, however, only in polished sections.

Magnetite and hematite, usually together, form many relatively small deposits in San Bernardino and eastern Riverside Counties. One of these, in the Eagle Mountains, is a commercial source of iron for the Kaiser steel plant at Fontana. These ores carry some disseminated apatite. Other deposits of considerable size occur near Dale, and in the Kingston Mountains, and scattered elsewhere through San Bernardino County. Few of these are at present under development.

San Bernardino and Inyo Counties, particularly, are characterized by numerous lead-silver deposits in the Panamint, Argus, Slate, and other ranges in the desert area. In addition to the Cerro Gordo deposit already mentioned, the deposits of the Darwin area, the old Ibex mine, and others, were worked in the early days for their silver ores. The minerals of these deposits were largely in carbonate ores, with lesser amounts of primary galena.

Vanadinite and descloizite, with wulfenite and some minor uranium minerals, are found in the Vanadium King mine at Camp Signal, near Goff's Station, San Bernardino County.

The schist in the Sierra Pelona, north of the San Gabriel Mountains, is locally characterized by the presence of some unusual minerals. For example, in San Francisquito Canyon, zones rich in mariposite or in clinozoisite are found. In the alluvial fans on the north side of Cajon Pass, the fragments of Pelona schist often carry piedmontite needles so abundant as to color the rock distinctly red. Associated with the piedmontite here is a coppery red mica, earlier called allurgite, but most probably a manganian muscovite.

A rather large pegmatite in Pacoima Canyon, in the San Gabriel Mountains, is distinguished by the presence of abundant crystals of zircon, as much as 2 or 3 inches in length, and by platy crystals of allanite, some imperfect individuals reaching a length of 12 inches.

Numerous small deposits of stibnite are found in the Havilah and nearby districts in Kern Canyon, San Emigdio Canyon, Jawbone Canyon, and other places largely in Kern County. In the Erskine Creek deposits, particularly, native antimony has been found in notable amounts.

A deposit of cassiterite, relatively small but rich, was found at Cajalco in Riverside County, probably in hydrothermal veins associated with greisen. This occurrence appears to have been completely mined out. Smaller deposits are found near Gorman, where cassiterite appears in disseminated grains, or stringers, and rarely in larger masses, associated with very minor amounts of ludwigite.

Fluorite has been found in fair-sized deposits at various localities in San Bernardino County, notably the Cave Springs area. Fluorite is an important component of the ores at Darwin, and also appears in veins in eastern Riverside County, north of Blythe. The Felix fluorite mine at Azusa, where veinlets of green fluorite are accompanied by galena, affords at least a fair collecting locality in Los Angeles County.

An extensive belt of talc deposits, in dolomitic limestones along or near intrusive contacts, extends, with interruptions, from the southern end of the Inyo Mountains at least as far as Silver Lake, near Baker.

Barite, in massive veins and as platy crystalline aggregates, occurs abundantly along the sea cliffs of the Palos Verdes Hills. It forms the gangue of massive veins carrying cinnabar and rare metacinnabarite at Red Hill, Orange County. Barite is also the principal gangue mineral at Lead Mountain, northeast of Barstow, where the galena ore is accompanied by abundant secondary hemimorphite.

Roughly developed "sand calcite" crystals can be found in poorly consolidated tuffaceous layers just north of Ricardo, in Red Rock Canyon.

Claudetite and arsenolite in well-formed crystals were found associated with realgar in tuff and ash deposits along the Colorado River, in eastern Imperial County.

Summary. The minerals found in California make the State justly world famous for number, variety, and scientific as well as economic importance of its natural products. Of its more than 535 species, including a large number of "firsts," many occur in southern California. The variety of mineral suites serves to emphasize the striking differences in geologic setting that can be noted in the State.

2. PROBLEMS OF THE METAMORPHIC AND IGNEOUS ROCKS OF THE MOJAVE DESERT[*]

By Thane H. McCulloh[†]

INTRODUCTION

The Mojave Desert region, as defined by Baker (1911, pp. 335-336), is the region of desert plains, mountains, and valleys comprising the extreme southwestern portion of the Great Basin (fig. 1). It lies entirely within California, including parts of San Bernardino, Los Angeles and Kern Counties, and embraces an area of approximately 160,000 square miles. Its climate is arid, and the drainage is interior.

Because much of the geology of this region is imperfectly known, any discussion of the regional aspects of the metamorphic and igneous rocks must take the form of a progress report. The relatively few published geological reports describe more or less widely separated areas, involve investigations of widely differing scales and qualities, and in general have not been coordinated parts of any broad, systematic program of research. Knowledge of the geology thus is peculiarly spotty, and some apparently critical areas and subjects have been completely neglected. Present knowledge provides a basis for some conclusions, but at the same time it points to numerous problems awaiting solution. This paper is written in an attempt to focus attention upon some of these interesting unsolved problems, as well as to collate the conclusions already reached by various workers.

PRE-TERTIARY METAMORPHIC AND IGNEOUS ROCKS

General Statement

Pre-Tertiary metamorphic and igneous rocks crop out over approximately 25 percent of the region. With the exception of Quaternary alluvium, which covers about 60 percent of the region, no other group of rocks is as important areally. They form virtually the only record of a long and involved pre-Tertiary history. They also form the foundation and framework for the Tertiary and Quaternary stratigraphy and structure, the complexities of which have been recognized only in recent years, and they can be expected to yield information that should clarify some of those complexities.

The topics to be considered here are: 1) the problems of the ages and correlations of the metamorphic rocks, and the related problems of pre-Tertiary stratigraphy and paleogeography; 2) petrology of the metamorphic rocks, and the causes of the metamorphism; 3) structures of the metamorphic rocks, and their relation to metamorphic and igneous activity; 4) the pre-Tertiary volcanic rocks; 5) the pre-Tertiary intrusive rocks; 6) ages and correlation of the plutonic rocks.

Ages and Correlations of the Metamorphic Rocks

Pre-Cambrian Rocks. North and northeast of the Mojave Desert, and in its eastern portion, well known Paleozoic sedimentary sections rest in different localities upon pre-Cambrian sedimentary, metamorphic, and igneous rocks. The pre-Cambrian rocks have not been studied extensively, but the following facts are known.

Thick sections (up to 11,000 feet) of practically unmetamorphosed "younger pre-Cambrian" Pahrump sedimentary rocks have been described from the Kingston Range[29][‡] (Hewett, 1940), and from southern Death Valley (Noble, 1934; Kupfer, 1951; Wright, 1952). Noble writes that in the latter area[27] these "Algonkian" strata rest unconformably upon "Archean" schist, gneiss, and granitic rocks. Kupfer, on the other hand, reports that in the Silurian Hills[30] the unmetamorphosed sedimentary rocks grade into feldspathized, intruded, and metamorphosed rocks which previous workers called "Archean." More work is needed to reconcile such statements as these.

Murphy (1932) and Hopper (1947) describe thick sections of dynamothermally metamorphosed pre-Cambrian sediments from the Panamint Range. "Archean" gneisses, schists, marble, gneissoid granitic rocks, and migmatites underlie Cambrian or Pahrump strata in much of the eastern Mojave Desert, east and south of Death Valley. Such rocks have been described by Hazzard and Crickmay (1933) from the Marble,[32] Ship,[33] and Providence Mountains,[34] by Noble (1934) from the Black Mountains and Amargosa Range,[28] by Hazzard and Dosch (1936) from the Piute[36] and Old Woman Mountains,[37] and by Hewett (1940) from the Kingston Range.[29] The great variety of metamorphosed sedimentary and associated pre-Cambrian intrusive rocks occurring in these areas, and the local great thicknesses of metasediments (for example the Essex series of Hazzard and Dosch, 1936), strongly suggest a complicated history for the "Archean" rocks. Furthermore, the simple classification of the "pre-Cambrian" rocks as "Archean" if they are intensely metamorphosed and "Algonkian" if they are mildly metamorphosed may well be open to some question.

The relation of the "Archean" gneisses to the pre-Cambrian metasediments of the Panamint Range is unknown. The latter were divided by Hopper (1947), in part following Murphy (1932), into three units, the Telescope group, Surprise formation, and Panamint

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[‡] Numbers following geographic names are shown in figure 1 at the locations of the geographic features mentioned.

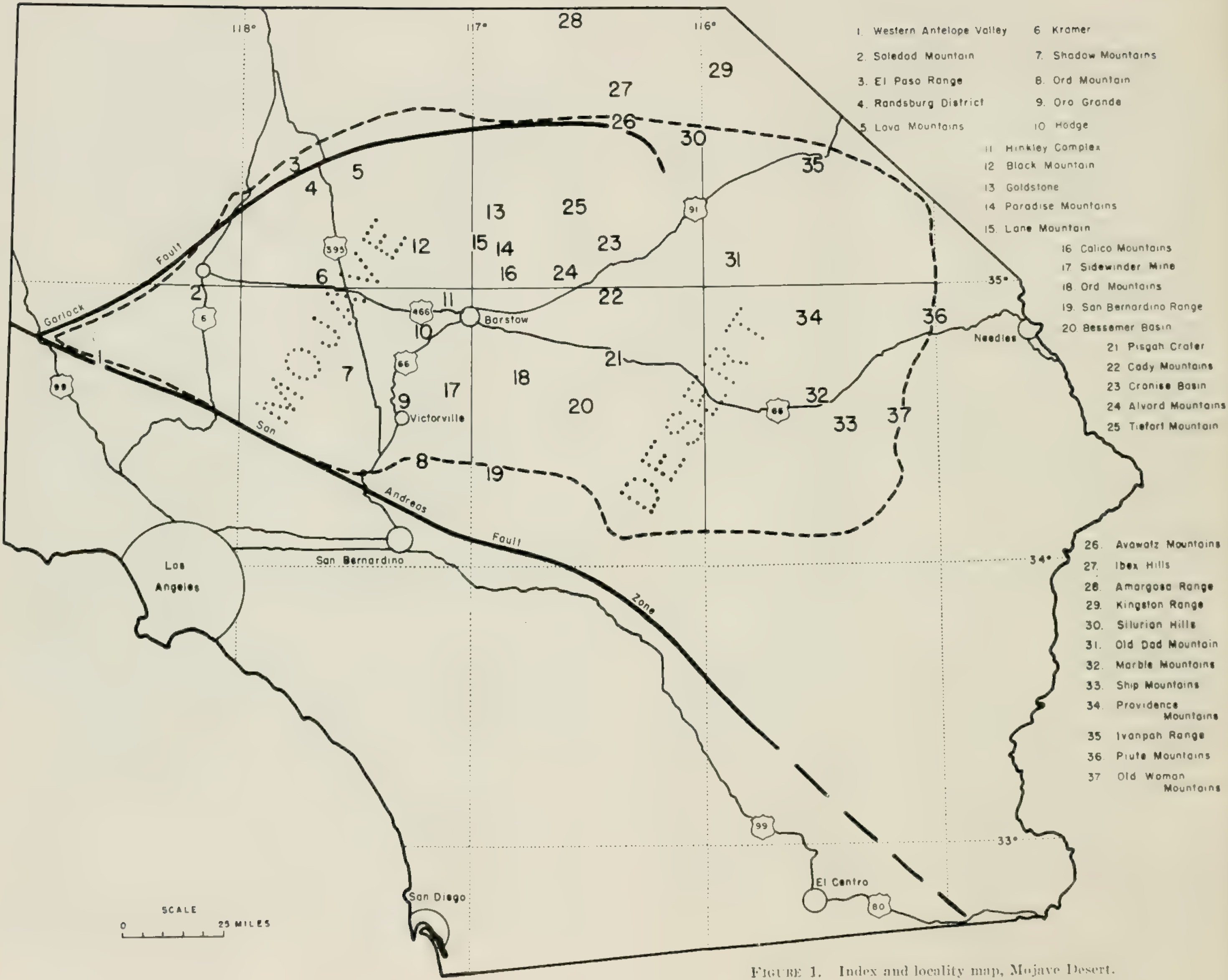

FIGURE 1. Index and locality map, Mojave Desert.

metamorphic complex, from youngest to oldest. Noble (1934, p. 174) has suggested that the Telescope group may correlate with the "Algonkian" Pahrump strata.

The author feels that the available evidence suggests that the pre-Cambrian rocks of the eastern Mojave Desert and the region to the north record a complex history of events separated by space and time. Thus far only hints of that history have been deciphered, but enough is known to suggest that the most promising areas for further study lie in the Panamint Range and in the southern Death Valley region.

In contrast to the situation in the eastern Mojave Desert, no early Paleozoic strata have been recognized in the central and western Mojave Desert. There the base of known Paleozoic rocks apparently has not been seen, and no rocks are proven to be unquestionably pre-Cambrian. Figure 2 shows the portions of the Mojave Desert in which the base of the Paleozoic has been mapped or where such rocks have been seen resting unconformably upon pre-Cambrian rocks. Clearly a pre-Cambrian age assignment for a given rock of the central or western Mojave Desert cannot be based upon any stratigraphic evidence now available.

The known Paleozoic rocks of the central and western Mojave Desert are dynamothermally or thermally metamorphosed sedimentary and volcanic rocks which are locally, but commonly, migmatized and injected near igneous contacts. They range from highly foliated to practically unfoliated. Petrologically similar rocks that have yielded no fossils are questionably assigned to the Paleozoic or Mesozoic.

In the same region with these known and probable Paleozoic rocks, are considerable areas of strongly foliated schists and gneisses of unknown age. Examples are the Rand schist and Johannesburg gneiss of the Randsburg district [4] (Hulin, 1925, pp. 1-29), and other rocks that have been observed by Gardner (1940, p. 264) in the Bessemer basin,[20] and by the writer in the Alvord Mountains,[24] Tiefort Mountains,[25] and Cronise basin.[23] These rocks, some of them granitic gneisses, are more highly deformed and more extensively altered than most of the proven Paleozoic rocks of the central Mojave region, and they are similar in appearance and petrology to some of the "Archean" rocks of the eastern Mojave. They have been termed pre-Cambrian by various investigators because of these similarities, or because of their petrologic contrasts with known Paleozoic metamorphic rocks. Although these age assignments may prove to be correct in some or all instances, it should be kept in mind that, at present, trustworthy stratigraphic evidence of pre-Cambrian age is lacking in the central and western Mojave Desert. As outlined below, some of these rocks could be early Paleozoic instead of pre-Cambrian in age.

*Paleozoic Rocks.** In those parts of the eastern Mojave Desert where pre-Cambrian rocks are known to exist, they are, or were at one time, overlain by fossiliferous Paleozoic sedimentary rocks. The principal stratigraphic relations of these rocks, which are only locally metamorphosed in contact zones next to Mesozoic plutonic intrusions, are known from careful studies in several areas. The stratigraphic relations and lithologies are diagramatically shown in the columnar sections of figure 2. With the exception of the predominantly clastic lower part of the Cambrian, especially the thick clastic sections in the Nopah, Resting Springs, and Panamint Ranges (north and northeast of the Mojave Desert), these unmetamorphosed Paleozoic strata are predominantly carbonate sedimentary rocks. Clastic increments are relatively unimportant, and volcanic and pyroclastic materials are absent.

As in the case of the pre-Cambrian rocks, there is a striking contrast between the Paleozoic rocks of the eastern and central parts of the Mojave Desert. The known and probable Paleozoic rocks of the central Mojave are poorly understood, rarely contain identifiable fossils, and are dynamothermally or thermally metamorphosed on a regional scale. They occur as roof pendants and septa partially engulfed by Mesozoic plutons, and generally are complexly folded and faulted. Fossils thus far found and identified from these remnants of Paleozoic rocks range from Mississippian (?) (Woodford and Harriss, 1928, p. 270) to Permian (Bowen, 1954). No fossiliferous rocks older than Carboniferous have been reported to date.

Although most of the nine fossiliferous Paleozoic units known to the writer in the central Mojave Desert are limestone or marble, these rocks are generally associated with hornfelsed argillaceous dolomite and notable or predominant amounts of metamorphosed pelitic sediments (schist or hornfels), quartzite, meta-arkose, and meta-conglomerate. Metamorphosed volcanic rocks are minor but notable associates. The following are representative examples of thick sections containing metamorphosed clastic sediments: On the northeastern slope of the Calico Mountains 25,000+ feet of apparently conformable strata, of which at least half are late Paleozoic in age, consist of 60 percent metamorphosed clastic sediments, 24 percent meta-volcanics, and minor amounts of marble and lime-silicate hornfels (McCulloh, 1952, p. 1339). The type section of the Oro Grande series [9] (Hershey, 1902, p. 288; Baker, 1911, p. 336; Bowen, 1954) contains a large proportion of quartzite and schist. On the northern slope of the San Bernardino Range [19] the thick Saragossa and Arrastre quartzite formations (Vaughan, 1922, pp.

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* See also Merriam, Contribution 2, Chapter III

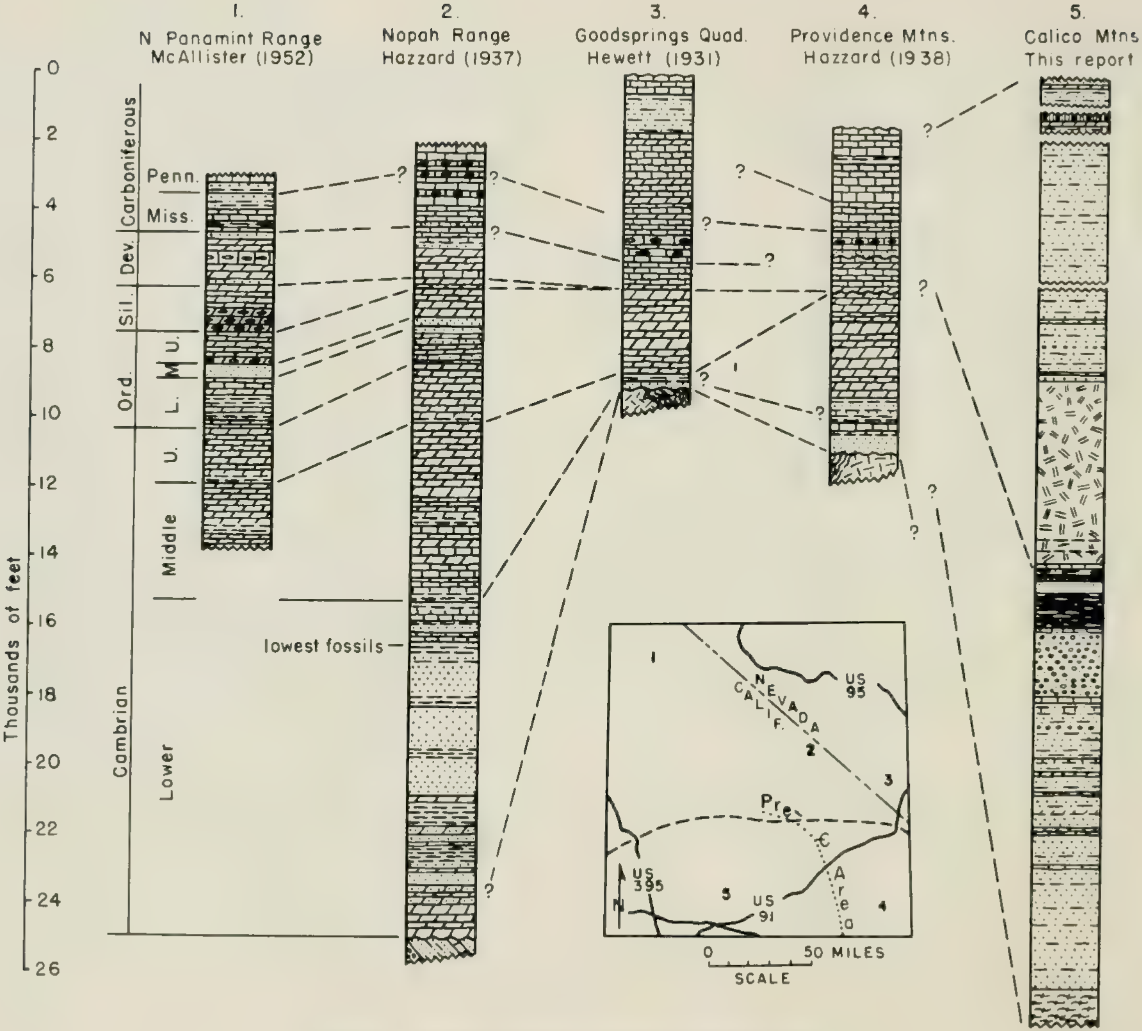

FIGURE 2. Tentative Paleozoic correlations, Mojave Desert.

352-361; Woodford and Harriss, 1928, p. 270) and associated Mississippian (?) Furnace limestone invite further attention.

The stratigraphic relations among these and the other known and suspected Paleozoic metamorphic rocks in the central Mojave Desert are so poorly understood that it would be pointless, and in fact misleading, for the writer to attempt to correlate from one imperfectly known section to the next. Inasmuch as such correlations constitute some of the more important and interesting unsolved problems of the region, however, specific facts concerning some of the better known sections will illustrate the kind of problems encountered, and might suggest possible answers to some of them.

In figure 2, the 25,000+ foot section of metamorphosed sedimentary and volcanic rocks of the northeastern Calico Mountains[16] is diagrammatically compared with the unmetamorphosed Paleozoic sections of the eastern Mojave Desert and the region to the north. Poorly preserved circular crinoid stems near the middle of this section suggest a late Paleozoic age, and heavy-shelled, ribbed mollusks in rocks which are either older or younger than the principal section indicate that 12,000+ feet of these predominantly clastic metasediments are post-Cambrian. As the entire post-Cambrian Paleozoic section of the eastern Mojave Desert is characterized by carbonate rocks which at no place total more than 8000 feet in thickness, the metamorphosed clastic sediments of the central Mojave Desert are evidence of a westward coarsening and thickening of a part of the younger Paleozoic strata. The thick meta-arkose units, characterized by detrital feldspar and accessory detrital zircon and tourmaline, and the local occurrence of granitoid pebbles in meta-conglomerate suggest that the source of these sediments was an area containing granitic or metamorphic rocks. Consideration of the distribution of known Paleozoic sedimentary rocks, coupled with their westward thickening and coarsening, strongly suggests that the source area was situated west of the site of deposition.

Bowen (1954) describes several metamorphic units, which he considers to be of Paleozoic age, from the Barstow quadrangle, southwest of the Calico Mountains. Only the two units that are fossiliferous are discussed in detail here.

The 2350+ feet of dolomite, marble, quartzite, mica schist, and lime-silicate hornfels (Bowen, 1954) just east of Oro Grande[9] were first described by Hershey (1902, pp. 287-288), who referred them to the Cambrian because of lithologic similarity to Cambrian quartzite in western Nevada. Baker (1911, p. 336) named these rocks the Oro Grande series, described them somewhat more fully, and cautiously refrained from correlating them. Miller (1944) reported finding crinoid stems in marbles of the type section, and suggested that the rocks are Carboniferous. Bowen has found more fossils near the type section, and has substantiated Miller's report. The relation of the Oro Grande series to the Calico Mountains section is unknown. The crinoid stems in both sections suggest a younger Paleozoic age for parts of each, but the sequence of lithologic units in the Oro Grande series has not been recognized in the Calico Mountains section. The thick quartzite and mica schist units of the Oro Grande series have no lithologic analogues in the Carboniferous sections of the eastern Mojave Desert, and provide further evidence of westward coarsening of the late Paleozoic strata.

The type section of the Fairview Valley formation[17] (Bowen, 1954), located in the eastern part of the Barstow quadrangle, consists of 6000+ feet of mildly metamorphosed conglomerate and hornfelsed fine-grained limy clastic sediments. The basal beds are reported by Bowen to rest unconformably upon unfossiliferous massive limestones and quartzites that are correlated with the Oro Grande series, and to contain well-rounded pebbles of porphyritic andesite and leucogranite in addition to some of quartzite and limestone. Clasts of granite, aplite, quartzite, and limestone are reported from strata higher in the section, and fossils collected by Bowen and others from limestone clasts in conglomerate that is high in the section are reported by C. W. Merriam (oral communication, 1953) to represent a typical Lower Permian fauna. A few fossils reportedly collected from the matrix of this conglomerate are also Permian, but may have been reworked from older sediments. Triassic (?) volcanic rocks are younger than this formation.

Bowen has concluded that the age of the Fairview Valley formation is Permian, but the writer considers that the available evidence permits an assignment to either the Mesozoic or the Permian. The unconformity reported by Bowen at the base of the formation is of considerable regional interest, especially in view of the granitic clasts in the overlying conglomerate. If the age of the formation can be unequivocally determined, a Permian or Mesozoic structural event of first-order importance will be dated. Whether or not the rocks can be dated more precisely than post-lower Permian does not alter the conclusion that major diastrophism, sufficient to allow erosion of considerable areas of Permian sedimentary rocks and important areas of pre-Permian granitic rocks, occurred in late Permian or early Mesozoic time. Without precise dating and more complete knowledge of the original areal extent of the formation, conclusions regarding the location of the source area can be only careful guesses. The factors that led to the conclusion that the clastic meta-sediments of the Calico Mountains Paleozoic section were derived from sources to the west can be extended, with somewhat less assurance, to the Fairview Valley formation.

Evidence now available thus indicates that the metamorphosed late Paleozoic strata of the central Mojave Desert are the thicker and more clastic equivalents of predominantly carbonate sections of the eastern Mojave Desert and the regions to the north. The more westerly sediments were deposited in a mobile area adjacent to a land mass from which large quantities of limestone, chert, quartzite, and granitic debris were being eroded for considerable intervals of late Paleozoic time. This land mass was situated somewhere to the west of the site of deposition. Determination of its position, boundaries, and area, and of the boundaries of the region of marine deposition comprises two of the most fundamental problems to be solved through a study of the metamorphic rocks of the Mojave Desert.

Several other areas of known or probable late Paleozoic rocks, when they have been adequately mapped, may well provide essential information to add to the rather nebulous picture described above. Such areas are the northern part of the San Bernardino Range,[19] Ord Mountain [8] south of Victorville (Noble, 1932, p. 356), the Shadow Mountains [7] northwest of Victorville, and the Goldstone area [13] 30 miles north of Barstow.

Pre-Carboniferous Paleozoic rocks have not been found in the Mojave Desert far west of the longitude of Baker. In the light of present knowledge, their apparent absence from the central and western Mojave Desert might be explained in several ways. First, pre-Carboniferous Paleozoic sediments may have been deposited, and subsequently so thoroughly and extensively metamorphosed that they have not yielded recognizable fossils. Second, such rocks may have been deposited, and then elevated and eroded prior to or during deposition of the younger Paleozoic strata. Third, such rocks may never have been deposited in this region.

The character, thickness, and distribution of the pre-Carboniferous Paleozoic strata of the eastern Mojave Desert (fig. 2) suggests that the area of deposition of these strata originally extended a considerable distance west of their present westernmost outcrops. That they may have covered some of the central Mojave Desert seems a plausible assumption. The abundance of sedimentary and granitic clastic debris in the younger Paleozoic rocks of the central Mojave Desert implies that much of any preexisting pre-Carboniferous Paleozoic cover was stripped from the source area, which lay an unknown distance farther west. If the older Paleozoic strata were similarly stripped from the central Mojave Desert, that event is not reflected in the predominantly non-clastic character of the Paleozoic sections in the eastern Mojave Desert and in the region to the north. These considerations lead to the tentative opinion that pre-Carboniferous sedimentary rocks were deposited in the area of the central Mojave Desert, and that they were probably not eroded prior to deposition of the known younger Paleozoic metamorphic rocks.

If this opinion is correct, perhaps some of the undated metamorphic rocks of the central Mojave Desert are actually early Paleozoic rocks in which fossils have not been recognized. For example, the folded, extremely foliated, and thoroughly recrystallized marbles, quartzites, and gneisses of the Hinkley Complex [11] (Miller, 1944, p. 79) could be of older Paleozoic age. Miller, in his original description, assigned these rocks, on unsatisfactory grounds, to the pre-Cambrian. Later (Miller, 1946, pp. 503-504) he correlated them, for almost equally unsatisfactory reasons, with the questionably Carboniferous metasediments of the Paradise Mountains.[14] If their markedly greater degree of deformation through shearing can be trusted to reflect a greater age, the rocks of the Hinkley Complex should be considered older than the fossiliferous late Paleozoic rocks of adjoining areas. As such, they could be either pre-Cambrian or early Paleozoic in age. Careful structural and stratigraphic studies will be needed to test this hypothesis. After much more careful work, similar arguments might be applied to some of the other undated metamorphic rocks of the central and western Mojave region, such as the Rand Schist [4] (Hulin, 1925, pp. 23-31) and the Hodge metavolcanic series [10] (Bowen, 1954).

Mesozoic Strata. Dated Mesozoic strata are rare in the eastern part of the region, and have not been proven, on paleontologic grounds, to exist in the central and western Mojave Desert. The only fossiliferous Triassic rocks thus far recognized are the 1000 feet of limestone, shale, and sandstone of the Providence Mountains [34] (Hazzard, 1936, p. 329). Hewett reports (oral communication, 1953) that Triassic and Jurassic formations have been mapped southwestward from the Goodsprings quadrangle, Nevada, as far as the Ivanpah Range,[35] where the Aztec sandstone is overlain by presumably Jurassic volcanic rocks.

Mesozoic metavolcanics (Ord Mountain group and Sidewinder metavolcanics) intrude and overlap the post-Lower Permian Fairview Valley formation in the eastern Barstow quadrangle [17] (Bowen, 1954), and are intruded by Mesozoic quartz monzonite in the Barstow quadrangle and in the Ord Mountains area [18] southeast of Barstow (Gardner, 1940, p. 270). The metavolcanics consist of a thick sequence of altered andesite, dacite, and rhyolite flows, and some volcanic breccias.

Petrology of the Metamorphic Rocks

Little information has been published about the mineralogy and petrology of the wide variety of metamorphic rocks discussed above, and a few general statements will suffice to summarize current knowledge and opinion.

The "Archean" rocks of the eastern Mojave Desert have been studied in detail at only one locality, in the Ivanpah Mountains [35] (Sharp and Pray, 1952), where they consist of a metamorphic complex of foliated feldspathic gneiss, quartz-mica schist, amphibole schist, and foliated pegmatitic bodies.

Silication of "Algonkian" siliceous and silica-poor dolomite to talc-tremolite-serpentine rock and tremolite-feldspar rock along the borders of "Algonkian" diabase sills in southern Death Valley[27] has been ascribed primarily to introduction of MgO, SiO_2, Al_2O_3, K_2O, and probably Na_2O from the diabase magma (Wright, 1952, p. 1347). Details of the mineral assemblages and textural relations are needed to reach conclusions concerning metamorphic grade or facies.

Aside from such pre-Cambrian contact metamorphism, the younger pre-Cambrian Pahrump strata of southern Death Valley are usually unmetamorphosed. However, the writer has observed that feldspathic sandstone has been recrystallized to biotite-quartz-plagioclase hornfels near contacts with quartz diorite on the northern slopes of the Avawatz Mountains.[26] Considerable work should be done to determine the areal distribution and grades of these metamorphic rocks, as well as the age of metamorphism. No data relating to the petrology of the reported gradation between Pahrump strata and the "Archean" gneisses in the Silurian Hills[30] (Kupfer, 1951, p. 1496) are published.

The Paleozoic and Mesozoic strata of the eastern Mojave Desert are only locally metamorphosed in thin contact zones adjacent to Mesozoic plutonic rocks, whereas the equivalent strata in the central Mojave Desert usually show evidence of one or more periods of regional thermal or dynamothermal metamorphism. So far as the writer knows, the only extensive petrographic study of metamorphosed Paleozoic rocks of any part of the central Mojave Desert has been his own work on the metamorphic rocks of the Lane Mountain quadrangle,[15] where two different periods of progressive metamorphism are discernible. An older, dynamothermal, metamorphism was particularly intense along pre-intrusive imbricate fault zones, where different rock types were recrystallized to various kinds of schists and amphibolites, characterized by shear folds and lineation (and elongation) parallel to the fold axes. The effects of a younger thermal metamorphism, unaccompanied by significant shearing, are manifested in the nearly uniform recrystallization of all rocks to hornfels, quartzite, marble, or amphibolite, depending upon original composition. The abundant minerals are plagioclase, orthoclase or microcline, quartz, calcite, wollastonite, diopside, hedenbergite, tremolite, hornblende, biotite, muscovite, scapolite, and grossularite. In rare rocks of appropriate composition forsterite, spinel, and cordierite have been found. All the mineral assemblages are appropriate to the cordierite-anthophyllite subfacies of the amphibolite facies. Preservation of relic stratification, clastic textures, and rarely of fossils indicates that the second phase of metamorphism was not accompanied by great shearing stress. The apparently stable association of quartz and calcite far from intrusive contacts, and their universal reaction to form wollastonite nearer those contacts, support the supposition that the thermal energy necessary for the metamorphism had its source in intrusive igneous masses.

Conclusions regarding regional distribution of metamorphic rocks of different grades must await further field and petrographic work. Reconnaissance of parts of the central Mojave region suggest that the metamorphic rocks of the El Paso Range,[3] Rand Mountains,[4] and Shadow Mountains[7] appear particularly worthy of such study at this time.

Structures of the Metamorphic Rocks

The metamorphosed Paleozoic sedimentary rocks of the central Mojave region were folded and faulted prior to emplacement of Mesozoic plutonic rocks. The Oro Grande series in the type area[9] and the roof pendants of the Lane Mountain quadrangle[15] contain accessible illustrative examples of such pre-intrusive structures. Bowen (1954) believes that two periods of pre-intrusive folds are discernible in the Barstow quadrangle. He concludes that rather gentle northeast-trending folds resulted from late Paleozoic orogeny, and that Mesozoic folding occurred along northwest trends. In the region north of the Barstow quadrangle, northwest- to northeast-trending folds appear to have been formed during a single period of deformation.

The significances of the foliation, tight recumbent folds, and lineation of such rocks as the Hinkley complex meta-sediments[11] and the Rand schist[4] are not known. The contrast between these and the usually mildly foliated late Paleozoic metamorphic rocks could be interpreted as the expression of a pre-Carboniferous period of dynamothermal metamorphism. On the other hand, the greater degree of deformation may be simply the result of differences in competence or structural position. In the absence of careful detailed mapping and regional study, the writer feels that no generalizations are justified. A fertile field awaits those interested in structural petrology.

The structures of the metamorphic rocks studied by the writer usually show no indication of origin through stresses imposed on their walls by forceful intrusion of igneous magma, even immediately adjacent to contacts with plutonic rocks.

Pre-Tertiary Volcanic Rocks

Although pre-Cambrian rocks are fairly widespread in the eastern Mojave Desert, volcanic rocks have not been reported among them. The unmetamorphosed Paleozoic sedimentary rocks of the eastern

Mojave Desert and the region to the north also contain no volcanic or pyroclastic material, but the metamorphosed section of the Calico Mountains[16] does contain important thicknesses of meta-andesite and meta-basalt in three widely separated zones (McCulloh, 1952). Further, the thick section in the El Paso Range[3] includes units of mildly metamorphosed volcanic rocks above and below a central fossiliferous zone that has yielded a Permian fauna (Dibblee, 1952).

Much work remains to be done to determine the time range of the Paleozoic volcanic rocks, and to determine the geographic limits of the area of volcanism. Moreover, it is desirable to establish the relationship between the area of volcanism and that of late Paleozoic clastic sedimentation. It appears significant that the Paleozoic strata of the eastern Mojave region are mostly unmetamorphosed carbonate rocks without volcanic material, whereas those of the central Mojave Desert occur in much thicker, regionally metamorphosed sections containing major proportions of clastic material, and associated with volcanic rocks. It also may not be accidental that large-scale intrusion of Mesozoic plutonic rocks was fairly well restricted to the central Mojave Desert and to the regions farther west.

The Lower Triassic sedimentary rocks of the Providence Mountains[34] (Hazzard, 1936, p. 329) are unaccompanied by Mesozoic volcanic rocks. However, coarse agglomerate overlies the Jurassic Aztec sandstone in the Ivanpah Mountains[35] (Hewett, oral communication, 1953), and similar rocks at Old Dad Mountain,[31] southeast of Baker, are described by Hazzard, et al. (1937, p. 279) as 1000 to 2000 feet of altered basic and acid lava flows, agglomerate, and tuffaceous (?) slates with marble, which are intruded by "Jurassic (?) granite." These investigators correlate the volcanic rocks of Old Dad Mountain with similar rocks at Ord Mountain,[18] and note that their age is "Triassic or Jurassic, rather than pre-Cambrian or Paleozoic—because a) the rocks lack the widespread high-degree metamorphism characteristic of the Archean and show no similarity with known Algonkian beds; b) no Paleozoic volcanics are known anywhere within the region; c) the rocks are intruded by Jurassic (?) plutonics having similar relations in the different areas." Gardner (1940, pp. 266-270) described the "Ord Mountain Group" of andesitic flows, tuffs, and breccia and hypabyssal intrusive rocks in somewhat greater detail, and repeated the reasons given by Hazzard, et al. for their Mesozoic age. Bowen (1954) correlates the post-Lower Permian Sidewinder metavolcanics of the southeastern Barstow quadrangle[17] with the Ord Mountain group, and concludes that they are questionably Triassic.

More precise dating and correlations of these rocks are desirable. Some of them are almost certainly Jurassic, and others may be Jurassic or Triassic. Their relations to Mesozoic metavolcanics outside the region, in the Inyo Mountains (Knopf, 1918, pp. 47-48) and in the Santa Ana Mountains (Larsen, 1948, p. 18), and to questionable or possible correlatives in the central Mojave Desert, such as the Hodge metavolcanics series[10] (Bowen, 1954), are prerequisite to an understanding of the regional geologic history.

Pre-Tertiary Intrusive Rocks

Pre-Cambrian intrusive or eruptive rocks have been specifically described from only three localities in the eastern Mojave Desert. The Fenner gneiss, a granitic augen gneiss exposed in the Piute[36] and Old Woman Mountains,[37] and at Chubbock on the Santa Fe Railway, was thought by Hazzard and Dosch (1936, p. 308) to have "—intruded Essex Series prior to metamorphism of both," and before deposition of Lower Cambrian strata. The "Algonkian" diabase sills of southern Death Valley[27] (Wright, 1952, pp. 1347-1348) have been mentioned above. Alkaline rocks, ranging from syenite to shonkinite, intrude a pre-Cambrian gneissic complex at Mountain Pass in the Ivanpah Mountains.[35] These rocks have been carefully studied (Sharp and Pray, 1952; Olson, et al., 1952) because of their association with veins and an intrusive carbonatite containing bastnaesite and other rare-earth minerals. No age assignment has been made, but recent radioactive age determinations of monazite suggest a pre-Cambrian age for the intrusive carbonatite and related alkaline rocks (D. F. Hewett, oral communication).

Paleozoic intrusive rocks apparently do not occur in the eastern Mojave Desert. In the central Mojave Desert, the presence of volcanic flows associated with Paleozoic metamorphosed sediments suggests that Paleozoic intrusive rocks are also to be expected, although none have been recognized to date.

The outstanding phase of intrusive activity evidenced in the Mojave Desert occurred in middle or late Mesozoic time, and resulted in the emplacement of enormous volumes of plutonic igneous rocks of normal calc-alkaline mineralogy. These rocks are probably more abundant in the basement complex of the central and western Mojave Desert than in the eastern part. They appear to be spatially and mineralogically related to the plutonic igneous rocks of the Sierra Nevada and Peninsular Ranges of California, and are of roughly the same age.

The most mafic Mesozoic rock examined by the writer is an almost black poikilitic perknite composed of nearly equal quantities of magnesian olivine, hypersthene, and hornblende with only about 15 percent of calcic labradorite. This rock occurs in a small patch of gabbroic rocks at the south end of the Paradise Range.[14] It grades through olivine-hypersthene-hornblende gabbro and hornblende diorite to areally more abundant biotite-hornblende quartz diorite.

These genetically related rocks are intrusive into Paleozoic metamorphic rocks, and are themselves intruded by hornblende-biotite quartz monzonite which grades into granodiorite. The latter rocks are intruded in turn by light gray biotite quartz monzonite or granite. This perknite-to-granite range of plutonic rock types, as found in the Paradise Range, encompasses all of the unaltered rock types, except dike rocks, thus far reported from the Mesozoic plutons of the Mojave Desert region.

Although it is known that the Mesozoic plutonic rocks of the Mojave Desert range in composition from nearly ultrabasic to very silicic, quantitative data on the relative abundances of the different rock types are lacking because of incomplete mapping. The author estimates, on the basis of reconnaissance observations, that leucocratic quartz monzonite or granite has an areal abundance many times greater than that of any other intrusive rock type, and that diorite and gabbro are far less abundant. The preponderance of leucocratic quartz monzonite over other rock types is reflected in the relatively large number of bodies of this rock type reported by various investigators from over the entire Mojave Desert. Examples include the Cactus granite (Vaughan, 1922, p. 363; Woodford and Harriss, 1928, p. 271; Miller, 1946, p. 472; Gardner, 1940, p. 273), Victorville quartz monzonite (Miller, 1944, p. 105), Atolia quartz monzonite (Hulin, 1925, p. 33), Teutonia quartz monzonite (Hewett, 1954), and White Tanks granite (Miller, 1946, p. 493). All of these units, and others that are unmentioned in the literature, are structurally, texturally, and mineralogically similar if not nearly identical. The significance of their similarities, and especially of their areal preponderance over the wide variety of more basic types, is worthy of careful study.

In the Lane Mountain quadrangle[15] rocks of the gabbro-quartz diorite complex are characterized by mineralogical and textural variability. Mineralogical composition varies notably, and sometimes rapidly, within individual plutons, and commonly the more silicic variants contain abundant irregular schlieren which grade into identifiable metamorphic inclusions near the pluton walls. Local gradational wall-rock contacts and evidence of replacement of wall rocks by hybrid quartz diorite, the gradations between schlieren and xenoliths, and compositional variability near contacts suggest that replacement and assimilation were important mechanisms in the development of this rock. On the other hand, alignment of platy inclusions in the plutonic rock parallel to the pluton walls, rather than to wall-rock structure, suggests viscous magmatic flow. In contrast to the diorite-quartz diorite, plutons of the leucocratic biotite quartz monzonite are characterized by textural and compositional uniformity. Inclusions are very rare except immediately adjacent to the usually knife-sharp contacts with metamorphic and igneous wall-rocks, where some of them can be seen to have been stoped by mobile homogeneous magma. Piecemeal magmatic stoping appears to have been the principal mode of emplacement of at least the peripheral parts of these plutons, some of which are of batholithic dimensions. Evidence of forceful intrusion of viscous magma is not usually seen, although local wall-rock mylonitization or crumpling at contacts with plutonic rock, and flow structures in the contiguous igneous rock, suggest that forceful intrusion occasionally played a part.

Ages of the Mesozoic Plutonic Rocks

The problem of the ages of the Mesozoic plutonic rocks of the Mojave Desert is part of the broader problem of the ages of such rocks throughout the southwestern Cordillera, including the western Great Basin, the Sierra Nevada, and the Peninsular Ranges of southern California and Baja California. Stratigraphic evidence within the Mojave Desert does not allow precise dating of the plutonic rocks. Hewett writes (1939, p. 1951) that at the eastern edge of the region "Mesozoic sedimentary rocks, culminating in Upper Jurassic sandstone, attain 8000 feet" in thickness and are involved in major thrust faulting. "An extensive sill of quartz monzonite, intruded on a major thrust fault,—" indicates that quartz monzonite was emplaced following diastrophism that involved Jurassic Aztec sandstone, and that the intrusive rock is therefore Upper Jurassic or younger. The exact age of the diastrophism that preceded intrusion is not known.

Comparable thrust faults and associated features, apparently in the same structural belt, were formed between late Jurassic and early Tertiary times in the Muddy Mountains, Nevada (Longwell, 1949, p. 965). Longwell has cited evidence which indicates that at least two phases of diastrophism were responsible for these structures, one in late Jurassic or pre-Bear River Cretaceous time, the other in Upper Cretaceous or Tertiary time. Probably we do not have sufficient stratigraphic data to decide whether the pre-intrusive thrust faults and associated structures of the eastern Mojave Desert were formed during either of the diastrophic phases dated in the Muddy Mountains. Therefore, the intrusive rocks themselves cannot be dated, on stratigraphic evidence, more closely than late Jurassic to early Tertiary, although they are most probably Mesozoic.

In the central Mojave Desert probable Triassic or Jurassic metavolcanic rocks are intruded by plutonic igneous rocks that are therefore late Mesozoic or Tertiary in age. The plutonic rocks of the western Mojave Desert, south of the Garlock fault, cannot be dated even this closely.

The discovery of radioactive minerals in plutonic rocks at several localities in the southeastern and central Mojave Desert gives hope that radioactive age determinations will provide additional and possibly more satisfactory bases for dating the intrusive rocks. Hewett reports (oral communication, 1953) that betafite from a granitic pegmatite in the Cady Mountains [22] has been determined to indicate a Jurassic age.

TERTIARY AND QUATERNARY IGNEOUS ROCKS

General Statement

Lavas, pyroclastic rocks, and hypabyssal intrusive rocks are areally important constituents among the Tertiary and Quaternary formations of the Mojave Desert. These rocks range in composition from basalt to rhyolite, and in age from middle Miocene, or perhaps older, to practically Recent. However, the petrologic and stratigraphic relations of many, perhaps even most, of these rocks are unstudied. The following problems of the Tertiary igneous rocks are discussed here: 1) distribution of volcanic rocks in space and time; 2) compositional variations; 3) hypabyssal intrusives; 4) volcanism and ore deposits.

Distribution of Volcanic Rocks

Tertiary volcanic rocks occur in discontinuous patches and strips over much of the Mojave Desert, from the southwestern corner of the region to, and beyond, its eastern edge. In the western Antelope Valley,[1] the westernmost portion of the region, Wiese and Fine (1950, p. 1644) describe about 5000 feet of andesitic lavas resting on granite 7 miles east of Quail Lake. These rocks reportedly grade upward into continental clastic sediments that may be equivalent to marine Miocene sediments that also rest on volcanic rocks farther west. Tertiary deposition in the westernmost Mojave Desert thus began with accumulation of a thick section of Miocene, or older, andesites.

In the Calico Mountains [16] of the central Mojave Desert, as much as 7000 feet of crudely stratified andesitic and dacitic tuff, tuff breccias, and agglomerate, interbedded with a few flows, is overlain by middle and upper Miocene lacustrine and fluviatile deposits with some interbedded tuffs and andesitic lavas. All these rocks are overlain unconformably by Pliocene (?) andesite, dacite, and latite flows. Farther west, in the vicinity of Black Mountain [12] north of Hinkley, Pleistocene (?) olivine basalt rests unconformably on the older Tertiary rocks (Baker, 1911, p. 366), and 30 miles southeast, near Ludlow, the practically uneroded Pisgah crater [21] is associated with a nearly Recent basalt flow. Thus, in one part of the central Mojave Desert, the rocks record a history of volcanism beginning at some time during or before the middle Miocene and continuing intermittently through late middle Miocene, upper Miocene, probably late Pliocene, and Pleistocene, into practically historic time.

In the El Paso Range,[3] at the northern edge of the western Mojave Desert, andesite breccia occurs near the base of the terrestrial lower Pliocene sedimentary section, and five lenticular flows of olivine basalt occur higher in the same lower Pliocene section, which is unconformably overlain by Pleistocene (?) basalt (Dibblee, 1952). Hulin (1925) identifies the last-named rock as augite-hornblende basalt, which is younger than the Pliocene (?) Red Mountain andesite of the Randsburg District.[4] Faunal evidence of a post-middle Pliocene age for the Red Mountain andesite has been discovered by paleontologists of the U. S. Geological Survey (D. F. Hewett, oral communication, 1953) in the Lava Mountains,[5] near the northeastern edge of the Randsburg quadrangle.

Numerous other occurrences of volcanic rocks in the Mojave Desert have been described by Hulin (1925, pp. 48-52), Hershey (1902), Simpson (1934), and Gardner (1940), but these rocks are so inadequately dated that discussion of their relations to the rocks already described is not worthwhile. However, these occurrences serve to indicate that, far from being restricted to a few parts of the region, Tertiary and Quaternary volcanic rocks are widespread over the entire Mojave Desert, and work on the task of differentiating and dating the numerous more or less separate episodes of volcanism has only begun.

Compositional Variations

Many factors, such as inadequate knowledge of the distribution of the volcanic rocks in space and time, absence of extensive petrographic descriptions of those rocks whose stratigraphic positions are known, and complete lack of chemical analyses, make it difficult to discuss compositional variations at this time. Existing data, however, suggest that there are no obvious simple trends of compositional change. Because of current advances in our knowledge of the Tertiary stratigraphy, largely the result of work by members of the U. S. Geological Survey, the problems of compositional variations of volcanic rocks extruded or intruded at different intervals during a considerable period of geologic time in this relatively large province are becoming more and more susceptible to careful systematic study.

Problems of the Hypabyssal Intrusives

Hypabyssal dikes, sills, and plugs, composed of holocrystalline to hemicrystalline basalt, andesite, dacite, latite, and rhyolite of Tertiary age, have been recognized in several parts of the Mojave Desert, particularly in the Randsburg District [4] (Hulin, 1925) and, by the author, in and near the Calico Mountains.[16] In the latter area these intrusive masses range in size from tabular dikes and sills only a few feet thick up to roughly circular plugs as much as 4000 feet across. The plugs intrude rocks of the basement complex, as well as folded stratified Tertiary volcanic, pyroclastic, and sedimentary rocks. Most are roughly circular or elliptical in plan, cut discordantly across the structures of the wall rocks, and have contacts that dip very steeply outward or steeply to gently inward. Funnel-shaped cross sections are fairly typical, and, in the larger discordant plugs, evidence of more than local wall-rock deformation is lacking. Flow layering is generally present in the intrusive rock, and near the contacts is conformable with the contacts. Wall-rock inclusions, especially of Tertiary rocks, are rare, and alteration of the wall rocks usually consists of local silicification around the periphery. The mode of emplacement of the larger hypabyssal intrusive bodies appears to have been by forceful intrusion to a limited degree, and mainly by intrusion into funnel-shaped near-surface openings that were probably formed by explosive widening of the shallower portions of the magma channels.

Tertiary Volcanism and Mineral Deposits

The principal production from the rich silver and gold mines of the Randsburg district,[4] the Calico Mountains,[16] and the area around Soledad Mountain [2] south of Mojave has been from epithermal veins and mineralized zones associated with certain of the Tertiary intrusive rocks. Hulin's (1925) account of the geology and ore deposits of the Randsburg quadrangle contains the only published detailed descriptions of the mineralogy, occurrence, and paragenesis of ore deposits of this kind (see also Gardner, Contribution 6, Chapter VIII).

Deposits of borate minerals occur in Tertiary sedimentary rocks at several localities in the Mojave Desert (see Mumford, Contribution 2, Chapter VIII). The colemanite deposits of the Calico Mountains [16] yielded a major share of California's borate production between 1884 and 1907, and the mines of the Pacific Coast Borax Company at Kramer [6] are currently providing most of California's production of this valuable resource. The possible relation between borate deposits and volcanism, either actual eruptions of lava or fumarolic activity, has been pointed out by Gale (1926, pp. 449-450).

The most recent descriptions of the several commercially important strontium deposits of the Mojave Desert are those of Durrell (1953), who concludes that the strontianite and celestite are usually genetically related to Tertiary volcanism.

Certain other mineral deposits of minor economic importance, such as bentonitic clays derived from Tertiary tuffs, and pumice for use in lightweight-concrete aggregate, obviously owe their origin also to Tertiary volcanic activity.

Acknowledgments. The writer gratefully acknowledges the assistance of the National Science Foundation, the University of California, and the U. S. Geological Survey in making possible publication of this manuscript. He also wishes to express thanks to D. F. Hewett and O. E. Bowen for providing unpublished data.

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3. THE BATHOLITH OF SOUTHERN CALIFORNIA[*]

By Esper S. Larsen, Jr.[†]

Location. The batholith of southern California occupies the core of the Peninsular Ranges from the vicinity of Riverside, California, southeastward to the southern tip of Baja California, a distance of about 1000 miles. The width averages about 70 miles in the northern part. The main northwestern body underlies an area of about 20,000 square miles, and the whole body an area of probably more than 40,000 square miles. This batholith is therefore larger than the batholith of the Sierra Nevada, and has the form of a great dike (fig. 1).

Age. From relations to fossiliferous rocks in northern Baja California the batholith is believed to be early Upper Cretaceous in age (Böse and Wittich, 1913; Woodford and Harriss, 1938). The following succession is found in California: fossiliferous sediments were deposited during Triassic time, and later were folded, mildly metamorphosed, and eroded; a great thickness of volcanic material and some sediments were deposited on the Triassic rocks; all of these rocks were greatly folded and mildly metamorphosed; many injections of the differentiating magma of the batholith followed, and the earlier magmas were largely crystalline before the succeeding ones were emplaced; erosion developed an old age surface and exposed the batholithic rock; sediments were laid down in Late Cretaceous time on the resulting surface.

The average determinations of the age from the lead-radioactivity ratios of zircons from five rocks were 100 ± 10 million years, and the age from two xenotimes was 105 million years. These data indicate Middle Cretaceous age.

The length of time between the injection of the gabbro and that of the final granite in the batholith is believed to have been of the order of 10 million years.

General Character of the Batholith. The batholith is composite; that is, it is made up of many separate injections. In the memoir by Larsen (1948) 20 subdivisions were made, and some of these did not represent single injections. However, nearly 91 percent of the batholith of the northern area is made up of five rock types or intrusions. The types that occur in small amounts are commonly confined to a few small bodies that lie near together, whereas the five main types are found in numerous rather large bodies in various parts of the area. The succession of intrusions is from gabbro to tonalite, to granodiorite, and finally to granite.

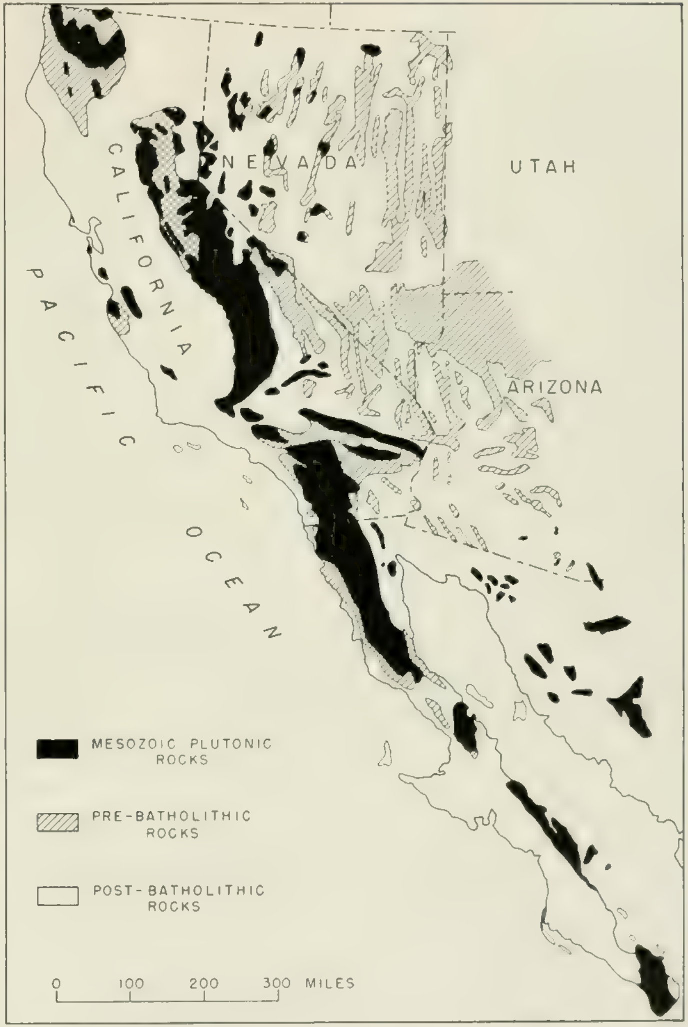

Figure 1. Outline map of California and Baja California, showing distribution of plutonic rocks of Mesozoic age

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[*] Publication authorized by the Director, U. S. Geological Survey.

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Approximate percentages of the area underlain by the various rock types are as follows:

San Marcos gabbro	7
Bonsall tonalite	28
Lakeview Mountain tonalite	20
Green Valley tonalite	12
Miscellaneous tonalites	3
Woodson Mountain granodiorite	24
Miscellaneous granodiorites	4
Granites	2

San Marcos Gabbro. This gabbro is characteristically variable (Miller, 1937), and contains anorthosite, calcic gabbro, norite, quartz-biotite norite, and corresponding rocks having a part or all of the pyroxene and olivine replaced by hornblende. The hornblende rocks contain a slightly more sodic plagioclase than the corresponding pyroxene or olivine rock. In texture they vary from fine-grained rocks with grains a millimeter or less in diameter to coarse-grained rocks with crystals several centimeters long. In general, the coarser-grained rocks are hornblende-rich. Generally, the fine-grained rocks cut the coarser-grained rocks, but the hornblende rocks cut the pyroxene rocks. The contacts of the types are in some places gradational, in others, sharp. Individual bodies of one kind of rock are for the most part small—a few tens of feet or much less across. In many places the bodies are dikelike in form. The biotite norite, the norite, and some of the related hornblende rocks make some fairly large masses of uniform rock.

The hornblende of these gabbros is clearly a very late or deuteric mineral, and in large part replaces pyroxene and olivine. A good illustration is the nodular norite half a mile east of Vista Grande, which has abundant nodules a few inches across of hornblende-free norite embedded in a matrix of hornblende gabbro in which the pyroxene has been replaced by hornblende (Miller, 1938).

The 10 analyses of the gabbros listed by Larsen (1948, pp. 50-51) show the variety and range of these gabbros.

Tonalites. Tonalites make up more than half of the rocks of the batholith, and the average rock of the batholith is a tonalite. Six types of tonalite have been mapped but only three types underlie large areas. In each of the three the chief rock is tonalite but the rocks grade to granodiorites. All three of these rock types are medium-grained biotite-hornblende rocks. The chief tonalite in the western area, the Bonsall tonalite (Hurlbut, 1935), is characterized by an abundance of dark, flat inclusions, or schlieren, derived chiefly from the gabbro. Locally, large inclusions of the older sedimentary rocks also are abundant. The common inclusions have the same minerals and textures as the host rock, but contain more biotite and hornblende. They are well oriented.

The Lakeview Mountain tonalite is much like the Bonsall but it contains few inclusions. The contacts between the two rocks are sharp. Near the contact with the Lakeview Mountain the inclusions in the Bonsall are oriented parallel to the contact. The Green Valley tonalite has a less sharply crystalline structure, especially with respect to the hornblendes. It contains few inclusions, but under the microscope the individuals of hornblende commonly show cores of uralitic hornblende with a few remnants of augite and borders of crystalline brown hornblende. Some of the larger plagioclase crystals have irregular, corroded cores of bytownite or anorthite surrounded by andesine, the normal feldspar of the rock.

Granodiorites. The Woodson Mountain granodiorite is a rather uniform, medium-grained rock. It carries a few dark inclusions. In most places it is massive, but near contacts with older rocks it becomes a gneiss or a streaked rock.

The other granodiorites are in small bodies and are commonly finer-grained than the Woodson Mountain.

Granites. Granite underlies only about 2 percent of the batholith area, and the Roblar leucogranite makes up most of the 2 percent. Several other types of granite, all in small local bodies, are present. The Rattlesnake granite (Everhart, 1951, pp. 87-88) underlies about 3 square miles of the Cuyamaca quadrangle, and is a coarse-grained rock with much muscovite and some garnet. It approaches a pegmatite in texture.

Mineralogy. Olivine is not an abundant mineral and is present chiefly in the calcic gabbros. Pyroxenes are abundant in many of the gabbros, but are found only rarely as cores to the hornblende in the tonalites. Iron-rich hypersthene is present in some of the potash granites. Hornblende is abundant in the gabbros as a late or deuteric mineral. In the tonalites it is an early constituent, and is the chief mafic mineral. It decreases in amount as the rocks become more siliceous, and is absent from the granites. Biotite appears with quartz, and nearly every rock with one of these minerals contains the other. Biotite is the chief or only dark mineral in the granites. Muscovite is rare as a primary mineral, and is confined to a few of the granites. The dark minerals and the enclosing rock have nearly the same ratio of $\frac{FeO}{FeO + MgO}$. The biotite may be a little richer in iron than the rocks. In the calcic gabbros this ratio is about 0.35; it increases through the other gabbros to the tonalite, and at the boundary between tonalite and gabbro it is about 0.60; it remains at about 0.60 across the tonalites and some of the granodiorites, then

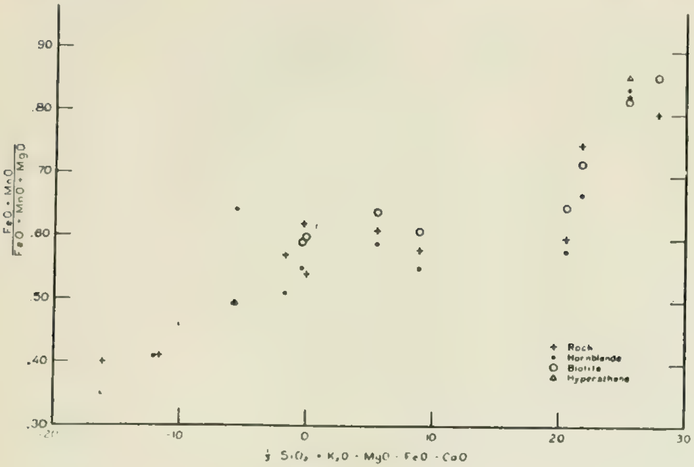

FIGURE 2. Ratio of $\frac{FeO + MnO}{FeO + MnO + MgO}$ in the mafic minerals and the enclosing rocks of the southern California batholith, plotted against the positions of the rocks on the variation diagram.

rises rapidly to about 0.85 in the granites (fig. 2) (Larsen and Draisin, 1948, p. 75).

Plagioclase ranges from anorthite in the calcic gabbros to oligoclase (An_{20}) in the extreme granites. The feldspars change regularly, as do the rocks.

Zircon is present in nearly all rocks containing quartz and biotite. It makes about 100 parts per million in the tonalites and granodiorites and much less in the extreme granites. Monazite and xenotime are found in the extreme granites with muscovite and garnet.

Every rock containing xenotime also contains monazite, but a few rocks contain monazite without xenotime. Monazite rarely exceeds 100 parts per million in a rock and xenotime rarely exceeds 20 parts per million. Apatite is present in most of the rocks to the extent of about 100 parts per million. In the granites it occurs in small amounts and is absent in many rocks with monazite and xenotime.

As much as 1 percent of sphene is present in some of the gabbros and tonalites, but some of the granites have little or none. The sphene has somewhat variable optical properties but is chiefly ordinary sphene. The sphene in the tonalite at Oak Grove is aluminous, and has lower indices of refraction and birefringence and larger axial angle than the common sphenes.

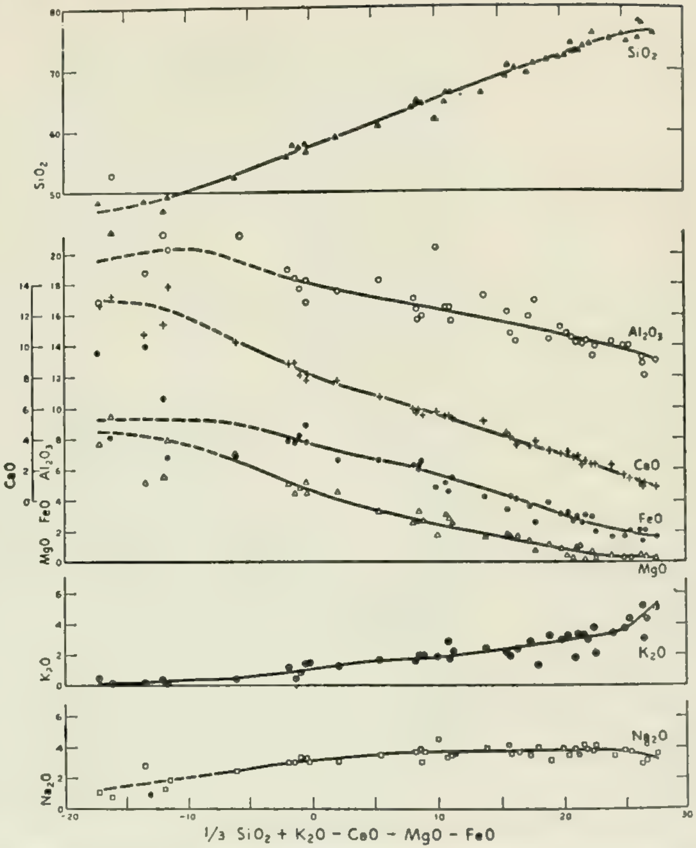

FIGURE 3. Variation diagram of the plutonic rocks of the Peninsular Ranges of southern California.

Chemical Composition. Thirty-six rocks, carefully selected to represent the main units and types, have been analyzed. They are plotted on a variation diagram (Larsen, 1948) in figure 3.

Trace Elements. Determination of some of the trace elements has been made by Mrs. E. L. Hufschmidt, of the U. S. Geological Survey, on most of the analyzed rocks and on some minerals from the rocks. The amounts of the trace elements have a wide range but show some trends. Approximate average values to show the trends are given in table 1.

Table 1. Approximate average content, in parts per million, of the trace elements in the rocks of the southern California batholith.

	Calcic gabbro	Gabbro	Tonalite	Grano-diorite	Granite	Average igeneous rock[1]	California compared with average
CuO	30	60	24	5	3	90	Low
MnO	1400	1500	1000	600	350	1300	Average
CoO	40	35	25	—	—	29	Average
NiO	34	18	15	—	—	100	Very low
Ga_2O_3	25	19	18	18	22	20	Average
Cr_2O_3	100 ±	100	21 ±	4	2	290	Very low
V_2O_5	700 ±	350	160 ±	90 ±	22	270	Low
Sc_2O_3	90 ±	70	12 ±	6	3	5	High
Y_2O_3	—	—	—	—	65	34	
La_2O_3	—	—	—	—	60	21	
ZrO_2	30 ±	60	150 ±	110 ±	220	260	Low
SrO	980	1200	900	450 ±	140	180	Very high
BaO	150	600	700	1100	1200	280	Very high
B_2O_3	—	50	26	—	—	7	High
Li_2O	22	35	25	70	75	140	Low
Rb_2O	15	80	170 ±	280	450 ±	340	Low
Cs_2O	—	—	14	30	—	8	Low
U	0.3	1	2	3	4	4	Very low

[1] Modified from Rankama and Sahama (1949).

As compared with the rock in which they occur, the perthite tends to concentrate Ga_2O_3, PbO, Sc_2O_3, BaO, Rb_2O and Cs_2O; plagioclase concentrates chiefly SrO; biotite concentrates PbO, CuO, MnO, Ga_2O_3, V_2O_5, Sc_2O_3, Y_2O_3, La_2O_3, ZrO_2, BaO, Li_2O, Rb_2O, and Cs_2O; and quartz contains only small amounts of the trace elements.

Weathering. The gabbro is the most resistant rock of the batholith, and it commonly crops out as dark or reddish hills with angular form. It rarely yields the huge boulders of disintegration that characterize most of the more siliceous rocks.

Most of the tonalites, granodiorites, and granites yield huge boulders of disintegration commonly made of hard rock and embedded in disintegrated material that looks much like the rock of the boulders but can be pulverized easily. There is little chemical difference between the two. The size and shape of the boulders are characteristic of the rock, and the boulders from the coarse-grained rocks are larger than those from the fine-grained rocks. In many places contacts between different rock types can be located from a distance from the character of the outcrops. The size and shape of the boulders are determined by the distribution of sheeting and joints in the rock.

Origin of the Batholith. The author believes that the parent magma of the batholith was formed in depth by the same forces that folded the crust during Cretaceous time and formed the mountain range in Baja California, and that this magma was gabbroic (near a tonalite) in composition. It differentiated by crystal fractionation, with some assimilation and other processes, to form the various rocks we see. From time to time during the crystallization of the magma, earth movements forced some of the differentiating magma toward the surface, thus yielding the various rocks now exposed.

A primary, relatively homogeneous gabbroic magma is believed to have formed at a considerable depth along the length of the mountain range during the later stages of folding. The same forces and movements that folded the rocks determined the layer in the crust that furnished the magma, and thereby determined the composition of the magma. This gabbroic magma was slowly differentiating, and at any given time in its history it had an upper part essentially the same throughout the length of the batholith as to chemical composition and kind and amount of suspended crystals or inclusions. From time to time diastrophism moved the magma slowly toward the surface. This diastrophism may have been local and may have furnished local bodies of magma, or it may have been widespread and have emplaced many bodies. The magma injected during any movement would have been uniform throughout the area. Such features as texture and character of inclusions would have been determined by details of the movement.

After the emplacement of the gabbro little further movement took place until the upper part of the magma had the composition of a tonalite. Then many local and several widespread movements emplaced the several tonalites. The earliest movement, which did not greatly shatter the wall rock, emplaced the Lakeview Mountain tonalite. Later movement emplaced the Bonsall tonalite, and still later stages of this movement shattered the wall rock and mixed abundant inclusions in with the magma. Any siliceous inclusions were probably dissolved, but inclusions of gabbro were softened and flattened by reaction with the magma.

Another widespread movement shattered the wall rock and embedded inclusions throughout the moving magma. The gabbro inclusions were softened and then, by later movement, disintegrated, and crystals were rather uniformly scattered through the magma. Cooling then brought about recrystallization before the calcic plagioclase and augite crystals were completely reworked. Thus was produced the Green Valley tonalite.

After continued crystallization of the magma, later movements emplaced the Woodson Mountain and other granodiorites.

Zoning. The preceding descriptions apply to the western part of the batholith. The eastern part, seen only in reconnaissance, appears to be made up of tonalites of several kinds and some

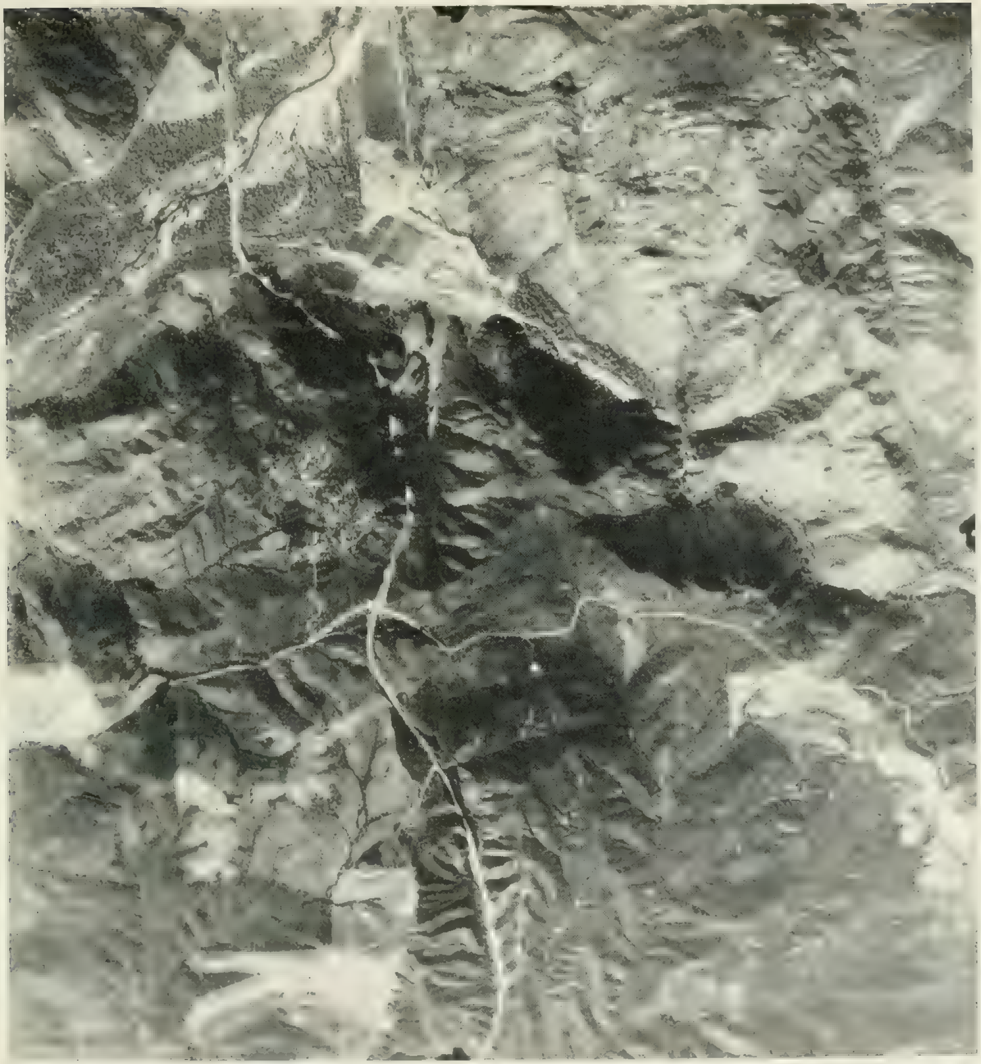

FIGURE 4. Typical batholith rocks as seen from the air about 5 miles northeast of Bonsall. The area in top (north) half of view is underlain chiefly by leucogranodiorite, and most of the remainder is underlain by tonalite. Note the patterns of joints, and the control of some drainage by jointing. San Luis Rey River at upper left, and Lancaster Mountain at upper right.

related granodiorites that are low in potash feldspar. These rocks contain lower percentages of dark minerals and potash feldspar than the rocks of the western part of the batholith, and they are lower in K_2O, FeO, MgO, and higher in SiO_2 and Al_2O_3 than the rocks farther west.

The scattered bodies of granitic rock in the desert ranges east of the Peninsular Ranges are chiefly granodiorite and quartz monzonite, and are higher in K_2O, Na_2O, and Al_2O_3, and lower in SiO_2 than the rocks of the main batholith.

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4. MIOCENE VOLCANISM IN COASTAL SOUTHERN CALIFORNIA

BY JOHN S. SHELTON *

INTRODUCTION

Miocene volcanic rocks occur in the marine Tertiary sediments of many parts of California, and Taliaferro (1941, pp. 142-4) has given special attention to them in the central and southern Coast Ranges. The purpose here is to summarize what is known of their occurrence farther south in the vicinity of the Los Angeles and Ventura basins.

The distribution of Miocene volcanic rocks in this part of southern California is shown in figure 1, which has been compiled with minor modifications from the published and unpublished sources listed at the end of this paper. Not all geologists agree concerning the detailed shapes of many of the exposed masses of volcanic rock, or even concerning the question of whether some of them are intrusive or extrusive. This arises partly from poor exposures and partly from the nature of the rocks themselves. In the western Santa Monica Mountains and Conejo Hills, many of the areas of presumedly extrusive rocks in figure 1 are known to contain dikes and interlayered sediments that are not shown on the map.

The volcanic rocks of the Conejo Hills and adjacent parts of the Santa Monica Mountains have been named the Conejo volcanics (Taliaferro et al., 1924, p. 800), and those in the vicinity of Glendora and Pomona, about 60 miles to the east, have been named the Glendora volcanics (Shelton, 1946); the term El Modeno volcanics is being proposed (Schoellhamer et al., in press) for those east of Orange (fig. 1).

Special appreciation is here expressed to Thomas L. Bailey, Cordell Durrell, A. O. Woodford, John A. Forman, and to geologists of several oil companies for their assistance in supplying information and or critically reading the manuscript.

FEATURES OF OCCURRENCE

Distribution and Volume. Surface outcrops of Miocene volcanic rocks are known from the areas shown by stippled and solid patterns in figure 1. The stippled areas are known to contain some intrusives, and details in the solid areas are somewhat uncertain. Tuff beds in the upper Miocene part of the section are not included. The total outcrop area includes more than 180 square miles of extrusive rocks and 28 square miles of intrusive rocks. Outside the area of figure 1, related volcanics are less widespread; generally those to the south and east are basic in composition, and are difficult to date, whereas those to the north and west are more silicic than the average of those shown in figure 1. In the northwest direction the next comparably extensive areas of outcrop lie northwest of San Luis Obispo.

Approximate maximum thicknesses of exposed extrusive rocks are reported to be 2,280 feet on San Miguel Island, 4,700 feet on Santa Cruz Island, 8,000 to 10,000 feet in the western Santa Monica Mountains and Conejo Hills, and at least 2,000 feet in the area northeast and east of Glendora.

Also shown in figure 1 are the locations of 38 wells in the areas of the Los Angeles basin and the San Fernando and Oxnard plains; these wells have been selected to indicate the subsurface extent of Miocene volcanic rocks. One well (No. 24, northwest of Oxnard) is included because it bottomed in the Sespe formation without encountering volcanics, and is interpreted as probably indicating their limit in this direction. All the other wells reached, bottomed in, or penetrated volcanic rocks, many of which are interlayered with sandstones and shales. Some of these sediments contain middle Miocene fossils (see table 1).

Much less is known about the volcanic rocks encountered in wells than about those exposed at the surface. Except in certain areas (e.g., some recent activity near Oxnard), drilling usually is stopped before such rocks are penetrated very far, and samples generally are scanty and consist of material that is much altered. However, assuming essential continuity of the volcanics around the group of wells in the Oxnard plain and around those on the east and west sides of the Los Angeles basin, an extent of about 500 square miles can be added to the minimum of 208 square miles now exposed. If the deep central part of the Los Angeles basin, in which the likely horizons are out of reach of current drilling, also is occupied by volcanics, and if much of the San Fernando valley area is similarly underlain by such rocks, their total extent may well be greater than 1,000 square miles.

A few wells have been drilled into older rocks beneath the volcanics. In the ten of these listed in table 1, the penetration of volcanic rocks ranges from 125 feet to 3,720+ feet; in the six in the Los Angeles basin it averages 2,370 feet, in the two from the Oxnard Plain it is 770 and 806 feet, and in the two in the San Fernando valley it is 125 and 400 feet. Dips are not known for most of the occurrences, but the thicknesses represented are not likely to be much less than the figures given. All the other wells listed stopped either in volcanics or in sediments that could be interbedded with them.

The available data obviously constitute slim evidence on which to speculate regarding the volume of volcanic rocks, but perhaps the

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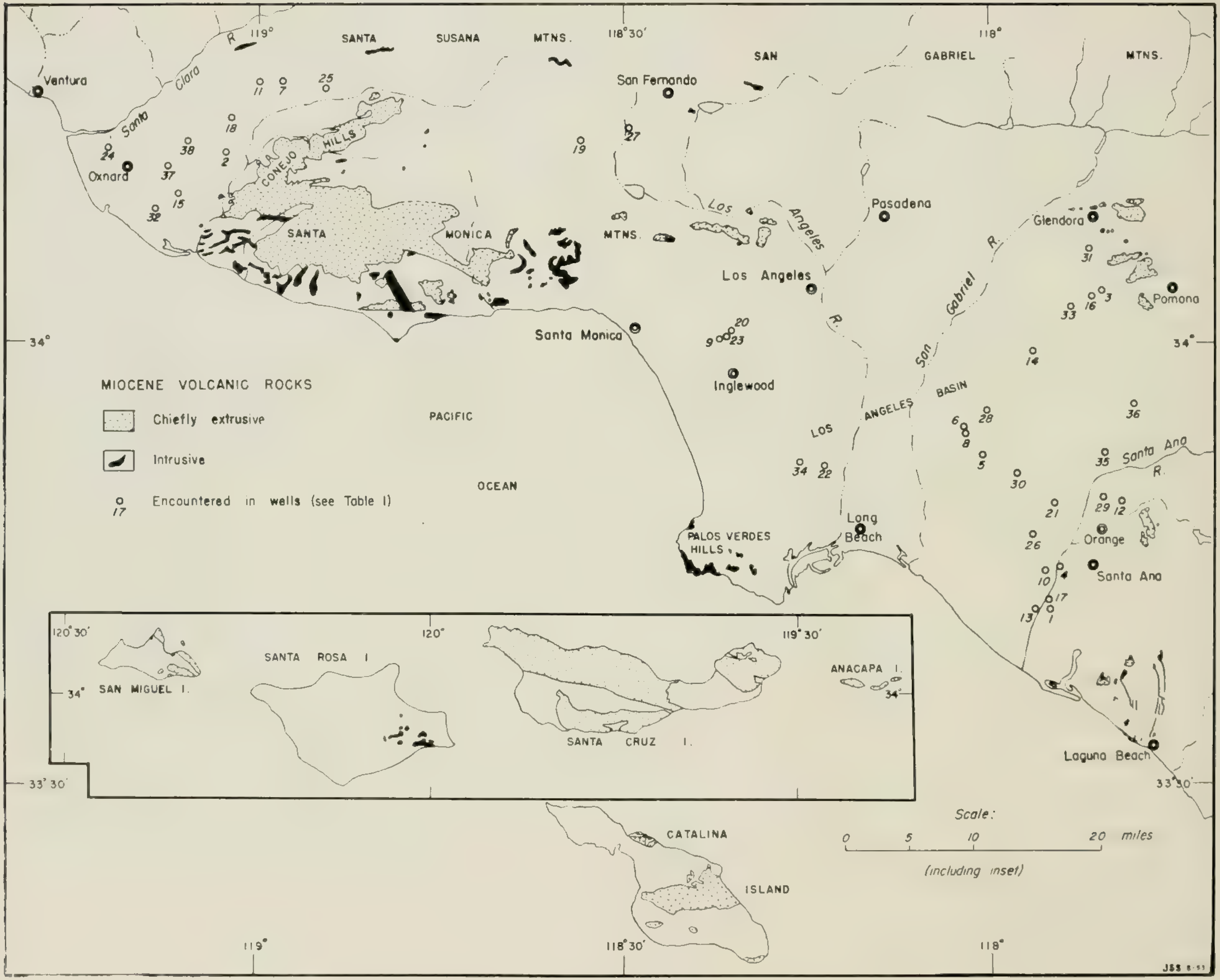

FIGURE 1. Map showing distribution of Miocene volcanic rocks in a part of coastal southern California.

order of magnitude can be indicated by assuming an average thickness of 1,000 feet over an area of 700 square miles. This would amount to approximately 140 cubic miles; twice as much does not seem unreasonable.

Character. Pyroclastic and brecciated rock types predominate, whether the volcanics are studied at the outcrop or from well cores, and regardless of their locality within the area covered by figure 1. Rocks in the range from breccia to tuff breccia probably are most common, and even some of the bodies interpreted as intrusive are brecciated. Massive flows probably are subordinate to instrusives in some western areas (e.g., Conejo Hills), but the reverse is true among the Glendora volcanics.

The breccias and tuff breccias differ in coarseness and proportion of tuff matrix. At one extreme are probable autobrecciated flows, in which blocks of more or less vesicular lava are embedded in a similar matrix that is distinguished from the blocks only by slight differences in color and resistance to weathering. At the other extreme are large deposits composed essentially of tuff in which are scattered blocks as much as 15 feet across. Generally, however, these blocks are less than a foot across, make up about half of the total volume of the deposit, and correspond closely to the matrix in rock type. Individual blocks commonly differ in color as a result of differing degrees of deuteric alteration of their exterior parts. Many blocks in the andesitic tuff breccias of the Glendora volcanics show well-developed radial cooling cracks, which suggests accumulation while hot and hence a péléan type of eruption.

The flows range in thickness from a foot or two to probably more than 30 feet, although few exposures are complete enough to provide good detail. In the Glendora area the tops of some of the basalt flows are noticeably vesicular and oxidized.

The intrusives apparently range in form from sills and dikes to chonoliths. Poor exposures have led some geologists to interpret as one irregular mass what others have mapped as a cluster of small intrusions. Baked contacts are not uncommon, and may be present even where the intrusive rock is brecciated. In the Santa Monica Mountains many of the intrusives follow faults and branch where the faults branch, and the faults can be traced beyond these igneous wedges and lenses into areas where they offset the sediments. Other igneous bodies seem to be confined to fault intersections. Many of the dikes in both the Conejo and Glendora areas are vesicular or amygdaloidal.

Petrographically, more is known about the volcanic rocks of the Santa Monica Mountains and Glendora-Pomona areas than about those elsewhere. Fragmental andesitic and basaltic rocks predominate among the Conejo and associated volcanics, although rhyolitic rocks are known. Bailey (personal communication) reports that here the lower part of the series consists chiefly of medium- to light-gray and purplish-gray, fine-grained porphyritic hornblende andesites in which andesine is the common feldspar, although oligoclase and labradorite sometimes are observed. In general these rocks are succeeded upward by breccias, tuffs, and flows of augite andesite. The uppermost part of the section consists of hypersthene basalt and olivine basalt; the latter is distinctly vesicular, and forms the top unit of the sequence in the Conejo Hills. Subsurface data suggest that the upper basaltic series thickens southward at the expense of the lower andesitic rocks. The intrusives in this area are chiefly fine- to coarse-grained diabase and hypersthene diabase, which in some of the smaller bodies can be seen to grade into porphyritic basalt. Several large intrusive masses of porphyritic hypersthene basalt are known.

The Glendora volcanics are predominantly andesitic. The greatest volume of both tuff breccias and flows is composed of calcic andesite with labradorite phenocrysts and andesine in the groundmass. Hypersthene, or relicts of it, generally is present and forms as much as 8 percent of some rocks. Olivine basalt, normal andesite, and rocks of rhyolitic composition also occur. In 14 analyzed rocks the SiO_2 content ranges from 47.23 to 75.50 percent, but the most common types contain 59 to 63 percent. No over-all sequence of rock types is discernible; within the 7.3 square miles of outcrops, at least nine different mappable units are believed to lie with depositional contact upon the crystalline basement rocks.

The extrusive rocks east of Orange have an average thickness of about 300 feet (maximum 750 feet), and include a basal olivine basalt succeeded by palagonite tuff, calcic andesite tuff breccia, and calcic augite andesite flows and flow breccias.

The largest body of volcanic rocks on Santa Catalina Island is composed of augite-hypersthene andesite with labradoritic feldspar (Smith, 1897). On the south side of Santa Cruz Island are rhyolitic flows and pyroclastic rocks, and on the north side are basalts and andesites (Bremner, 1932). The intrusives on Santa Rosa Island are reported to be basalt (Kew, 1927), and the tuffs, breccias and minor flows on San Miguel Island are reported to be chiefly basalt and andesite (Bremner, 1933).

Samples of the volcanics from wells commonly are pyritic and much altered. Those that are large enough generally indicate fragmental accumulations, or at least brecciated flows. Many of the fresher samples are sodic, and suggest some spilitization.

Deuteric alteration of both extrusives and intrusives is almost universal, and common products include pyrite, chalcedony, and analcite.

Table 1.

Map number	Operator	Well	Elevation of top of volcanics	Known penetration (in feet) and character of volcanics	Volcanics reported overlain by	Volcanics reported underlain by
1.	Bandini Petrol. Co.	Segerstrom 1	—5,539 ±	1,300+ (?) Hypersthene-augite basalt, at least in part; much tuff breccia, probably andesitic.	?	Bottomed in volcanics (?)
2.	Calif. Petrol. Corp.	Arneil 1	—1,000	1,273+ Basalt and basalt breccia.	Low upper Miocene	Bottomed in volcanics
3.	Continental Oil Co.	Bayly 1	—1,023 ±	1,765 ± Probably chiefly andesite, largely fragmental.	Middle Miocene	Basement
4.	Continental Oil Co.	Santa Ana Comm. 1	—4,130 ±	200+ Altered basalts interbedded with middle Miocene sediments.	"Pico"	Bottomed in volcanics
5.	Gen. Petrol. Corp.	Heath 1	—11,062	288+ Basalt interbedded with sediments containing middle Miocene foraminifera.	Pliocene	Bottomed in volcanics
6.	Gen. Petrol. Corp.	La Mirada 46-1	—12,480 ±	47+	High middle Miocene	Bottomed in volcanics
7.	Gen. Petrol. Corp.	Las Posas-McBean 1	—3,052	770 Chiefly basalt breccias; some andesite, vesicular flows, and bentonite.	Low upper Miocene	Vaqueros (lower Miocene) sandstone
8.	Gen. Petrol. Corp.	Librown 1	—12,000(?)	600 ± Interbedded sediments and volcanics to bottom.	Upper Miocene	Middle or upper Miocene
9.	Gen. Petrol. Corp.	Sentous 1	—8,049	62 Probably basalt; altered; fine grained. Some interbedded sediments reported as middle Miocene.	Upper Miocene	Middle Miocene
10.	Gen. Petrol. Corp.	Was 1	—5,598 ±	300+ Basalt (?)	Pliocene	Bottomed in volcanics
11.	Humble Oil and Ref. Co.	Berylwood 1	—2,294	806 Chiefly basalt breccias; some andesite, vesicular flows, and bentonite.	Low upper Miocene	Sespe (Oligocene (?)) (unconformably)
12.	McKee Oil Co.	Kokx Comm. 8-1	—1,871	Unknown thickness; altered volcanic rock.	?	*Turritella ocoyana*
13.	Morton and Sons	Crew Comm. 1	—8,850 ±	850 ±	Upper Miocene	Bottomed in volcanics
14.	Morton and Sons	Rowland Ranch Estate 3-1	—7,140 ±	980 ± Diabasic basalt; 209 of diabase higher in the hole.	Upper Miocene (?)	Granite, etc.
15.	Mugu Syndicate	Utt 1	—3,977	298+ Basalt. 319+ Fragmental basalt with some andesite.	High Pliocene (unconformable)	Topanga shale and sandstone (probably interbedded)
16.	The Ohio Oil Co.	Legrand 1	—1,742	2,990 ± Chiefly andesite; some basalt.	Middle Miocene	Basement
17.	P. M. Girard	Mark Fisher 1	—5,165	450+ Fragmental andesites (?).	Repetto	Bottomed in volcanics
18.	Richfield Oil Co.	McFarland 1	—553	2,335 Altered, vesicular basalt and andesite (?) breccias and tuffs; possibly some interbedded sediments.	Upper Miocene Monterey	Temblor or Vaqueros
19.	Richfield Oil Co.	Mulholland 1	—3,560	400 Basalt, massive.	Middle Miocene Topanga	Middle Miocene Topanga
20.	Shell Oil Co., Inc.	Baldwin Hills Comm. 1	—13,022	158+ Andesite, near basalt.	Middle Miocene	Bottomed in volcanics
21.	Shell Oil Co., Inc.	Mathis 1	—4,714	1,074+ Basalt and tuff, with some admixed sand.	Upper or middle Miocene	Bottomed in volcanics
22.	Shell Oil Co., Inc.	Reyes 135	—10,852	1,106 Fine-grained andesite and/or basalt; largely fragmental.	Upper Miocene	Basement
23.	Standard Oil Co., Calif.	Baldwin Cienega 105	—7,733	About 38 percent of lowest 4,180 feet is volcanics.	Upper Miocene	Bottomed in volcanics or basement
24.	Standard Oil Co., Calif.	Eastwood 1	(No volcanics;	entered Sespe at —9,345 ±; T.D. 11,027)		
25.	Standard Oil Co., Calif.	Gabbert 1	—1,850?	Volcanics on ditch, mostly basalt.	?	Bottomed in Sespe
26.	Standard Oil Co., Calif.	Stanley Comm. 1	—8,000 ±	424+	Repetto or older (?)	

Table 1—Continued.

Map number	Operator	Well	Elevation of top of volcanics	Known penetration (in feet) and character of volcanics	Volcanics reported overlain by	Volcanics reported underlain by
27.	Standard Oil Co., Calif.	Woo 1	—7,799	125 Fragmental altered basalt.	Low upper Miocene (?)	Middle Miocene
28.	Standard Oil Co., Calif.	Woodward Comm. 1	—10,979 ±	196 ±	Upper Miocene	Middle Miocene or Sespe
29.	Standard Oil Co., Calif.	Zaiser-Brelje 1	—4,134	100 + Probably interbedded with sediments.	Upper or middle Miocene	Diabase, or ?
30.	The Texas Co.	Buena Park U-1-1	—8,763	182 + Fragmental, at least in part.	Miocene (?)	Bottomed in volcanics
31.	The Texas Co.	Covina 27-1	—365 ±	3,660 ± Andesite and basalt, fragmental and massive.	Middle Miocene	Bottomed in volcanics or basement
32.	The Texas Co.	Eastwood 1	—1,897	750 + Basalt and basalt breccia.	Pliocene	Bottomed in volcanics
33.	The Texas Co.	Garnier 1	—1,880	3,720 ± Basalt and andesite; spilite (?).	Middle Miocene	Mylonitic basement
34.	Union Oil Co. of Calif.	Callender 79	—11,257	455 ± Some interbedded platy shale.	Upper Miocene	Upper Miocene or middle Miocene
35.	Union Oil Co. of Calif.	Chapman 29	—7,617 ±	195 ±	Upper Miocene	Middle Miocene (?)
36.	Union Oil Co. of Calif.	Gaines 1	—5,169 ±	20 + Andesite (?); 552 ± of diabase higher in the hole.		
37.	Vaca Oil Co.	Livingston 1	—3,855	370 + Basalt and basalt breccia with streaks of sandstone near the base.	Upper Miocene	Bottomed in volcanics
38.	Western Gulf Oil Co.	Beardsley 1	—2,585	2,264 ± Basalt and andesite flows, breccia, and tuffs.	Low upper Miocene	Temblor or middle Miocene, with diabase intrusions

Our present knowledge of the province as a whole indicates that andesites predominate among the extrusives, with basalt and dacitic or rhyolitic rocks following in that order. The associated intrusive rocks are predominantly basaltic or diabasic.

Age. In most areas the intrusives cut only rocks that are older than upper Miocene; no undisputed instance of intrusion into upper Miocene sediments is known to the author.

The middle Miocene age of a large part of the extrusive rocks is well established. In the Santa Monica Mountains, in wells on both sides of the Los Angeles basin, and in outcrops in the Glendora area there are numerous examples of extrusive rocks interlayered with marine sediments that contain middle Miocene fossils (usually foraminifera).

More difficulty attaches to ascertaining the earliest and latest eruptive activity. Fine-grained ash falls are not uncommon in upper Miocene shales, and one occurrence of possible upper Miocene flows is known to the writer. These are reported as basaltic flows and breccias that occupy a small syncline northwest of Tierra Rejada, northeast of the Conejo Hills, where they rest on diatomaceous shales, tuffs, and conglomerates that contain an echinoid fauna reported by Woodring as upper Miocene in age (Bailey, personal communication). The suggestion has been made that these may be a product of later reworking. It must be admitted that the middle Miocene age of the extrusives is so generally accepted that in many occurrences, especially in wells, the top of the volcanic section is arbitrarily taken as the top of the middle Miocene. However, in the Santa Monica Mountains north of Malibu Lake, fossiliferous upper middle Miocene (Luisian) sediments rest unconformably on the volcanics (Elam, 1948).

The age of the earliest eruptions is still more difficult to determine. In many occurrences the base is not exposed, or the volcanics rest on crystalline basement rocks. In most wells drilling is stopped within the volcanics, or at least before unmistakable pre-volcanic rocks are reached. Bailey (personal communication) feels that most of the Conejo volcanics occur in the upper part of the Topanga formation (middle Miocene). Durrell (personal communication) believes that both the base and top of the volcanics are probably unconformities throughout most of the Santa Monica Mountains; the underlying sediments are generally early middle Miocene or older and the overlying sediments late middle or upper Miocene. However, Taliaferro (1924, p. 801) reports a thin layer of basalt in the Vaqueros formation on the south slope of Oak Ridge, and it is possible that some of the volcanics in the Santa Monica Mountains belong to the Saucesian foraminiferal stage (Elam, 1948), which probably means they are lower Miocene. In the western Santa Ynez Range, outside the area of figure 1, Dibblee assigns his Tranquillon volcanics to the uppermost lower Miocene (Dibblee, 1950, p. 34).

One is inclined to conclude, on the basis of present knowledge from the Los Angeles area, that the main volcanic episode was confined, according to the local terminology, to middle Miocene time, and that only local activity existed during late lower Miocene and early upper Miocene times. Possibly the volcanic rocks in parts of the Santa Monica Mountains are slightly older than those farther west and east.

SUMMARY AND INTERPRETATION

In general character, age, and distribution, the volcanic rocks shown in figure 1 suggest at least a part of a volcanic province. Despite some loss by subsequent erosion, the extrusives and associated shallow intrusives probably represent several hundred cubic miles of magma—perhaps twice the volume of the San Franciscan volcanic field of northern Arizona.

The volcanic rocks that are interlayered with marine sediments show that much of the lava probably was poured out on the sea floor, or from vents close enough to it so that accumulation took place under water. Many details of the rocks bear this out. In some places fine-grained, more or less tuffaceous sediment is intimately mixed with the volcanics in such a way as to suggest the squeezing of mud into poorly defined fractures. Sandstone dikes several hundred feet long are present in volcanics of the Glendora South Hills, and pillow structure is locally well developed in the Santa Monica Mountains and Glendora volcanics. The presence of palagonite and fossiliferous tuff, as well as the altered state of many well cores probably denote submarine accumulation.

Some of the occurrences in the Palos Verdes Hills have been termed intrusive pépérites (Macdonald, 1939). The brecciation of some of the intrusives may tell the same story. During the late stages of accumulation of the Glendora volcanics, the shoreline probably was about a mile west of Pomona, because southwest of this there is abundant evidence of submarine accumulation, whereas northeast of it these characteristics are missing and there is some evidence of terrestrial *nuée ardente* eruptions in volcanic rocks believed to be of the same age.

Adequate source fissures or vents for all these volcanics have not been found. Probably some of the associated intrusive masses represent feeders, at least locally. A few outcrops in the Glendora area and one in the Conejo Hills suggest former vents. If hot péléan clouds accumulated on land in the area east of Glendora, at least one good-sized volcano probably lay in that direction. Aside from this, the variety and distribution of the rocks suggest numerous small vents and or fissures, rather than a few large sources. Perhaps the scene resembled Vesuvius and the Phlegraean Fields around the Bay of Naples today.

The Los Angeles basin is an area of locally derived Cenozoic sediments at least 25,000 feet thick, and as now exposed is a structural depression approximately 60 miles long and 40 miles wide. The most pronounced cycle in its history began in middle Miocene time and reached a climax of depth and localization during the upper Miocene and Pliocene. The climax of Miocene volcanism in southern California thus corresponds fairly closely with the beginning of the period of maximum growth of the basin, a phenomenon parallel to the history of many geosynclines (Knopf, 1948). But perhaps rather than a baby geosyncline, we have here just another unstable segment in the tectonically and volcanically active rim of the Pacific basin.

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5. PEGMATITES OF SOUTHERN CALIFORNIA[*]

By Richard H. Jahns[†]

INTRODUCTION

For many years the southern California region has attracted the attention of geologists interested in pegmatites and pegmatite deposits, largely because of the well-known gem and lithium occurrences in San Diego and Riverside Counties. These world-famous pegmatites have been so often noted or described in the literature that they commonly are regarded as typical of the pegmatites in the region, even though this actually is far from the case. More than 90 percent of all published contributions on California pegmatites deal with the gem-bearing dikes of San Diego County alone!

It is the main purpose of this brief paper to summarize the distribution, occurrence, composition, and structure of all the known pegmatites in southern California, and to discuss several aspects of their geologic and economic significance. Much of the information has been obtained from the published record, a sampling of which is included in the list of references at the end of the paper. In larger part, however, the writer has found it necessary to draw from the results of his own observations, many of which were made in reconnaissance and hence are not wholly satisfactory as a background for generalizations. This qualification with respect to basic data plainly underlies the summary and discussions that follow.

The pegmatites of southern California can be divided into three major categories in terms of their general form and mode of occurrence:

1. Very small stringers, lenses, and pods of gabbroic and, in a few areas, more granitic composition, that generally appear to have been formed as segregations within masses of genetically related igneous rock.
2. Small, irregular masses, of tonalitic to granitic composition, that form layers, lenses, pods, branching swarms, and stockworks in *lit-par-lit* gneisses and other hybrid rocks, as well as in contact zones between masses of igneous rocks and older rocks that flank or surround them.
3. Small to very large individual masses, of tabular to pod-like form and tonalitic to granitic composition, that ordinarily occur in igneous and metamorphic rocks.

For the sake of brevity, the pegmatites of these three categories are hereinafter referred to as segregation masses, complexes, and discrete pegmatite bodies, respectively. These terms are of necessity much generalized, as each category includes pegmatite bodies of various forms. Further, the terms are intended to be mainly descriptive, and hence to involve a minimum of genetic implication. As might be expected, nearly all gradations can be observed among these three major types of pegmatites.

The distribution and occurrence of pegmatites in southern California are summarized in table 1. Those masses that form the complexes are both widespread and locally abundant. They constitute by far the largest part of the pegmatite material in the region, but they have received little detailed attention from petrologists and other investigators. The segregation masses are considerably less abundant, although they are more widespread than published accounts of southern California geology might suggest.

By far the best known pegmatite bodies in the region represent the third category, which includes most of those with complex composition and spectacular mineralogy, and all of those that have yielded commercial quantities of economically desirable minerals. Some of the discrete bodies are very large, and many are structurally complex. These and other features of unusual interest are reflected in the attention given to the pegmatites of this category in the discussions that follow.

SEGREGATION MASSES OF PEGMATITE

Pegmatite masses of the segregation type are locally abundant in the Peninsular Range province (fig. 1), where they occur mainly in gabbroic rocks of the southern California batholith. They also are present in the western San Gabriel Mountains, in a few other, much smaller areas in the Transverse Range province, and in parts of the southern Sierra Nevada. Several scattered occurrences are known from the Mojave Desert and Basin-Range regions.

All of these pegmatites occur in igneous rocks to which they appear to be closely related in composition, age, and genesis. They appear as stringers (fig. 2), dikes, and pod-like masses (fig. 3) that are simple to highly complex in form. They rarely are more than 15 feet long, and most are less than 5 feet in maximum dimension. Contacts with the host rock are sharp to gradational, and the most blended contacts are typical of the most irregular masses of pegmatite.

Most of the segregation pegmatites are gabbroic in composition, and consist chiefly of hornblende and calcic to intermediate plagioclase in various proportions. Other mineral constituents include biotite, pyroxenes, apatite, magnetite, chlorite, epidote, and, rarely, quartz and alkali feldspars. Segregation masses of more granitic composition also have been observed, mainly in coarse-grained, felsic intrusives in parts of the Sierra Nevada and several mountain ranges of the eastern Mojave Desert. These pegmatites consist chiefly of perthite, quartz, and sodic plagioclase, with or without subordinate

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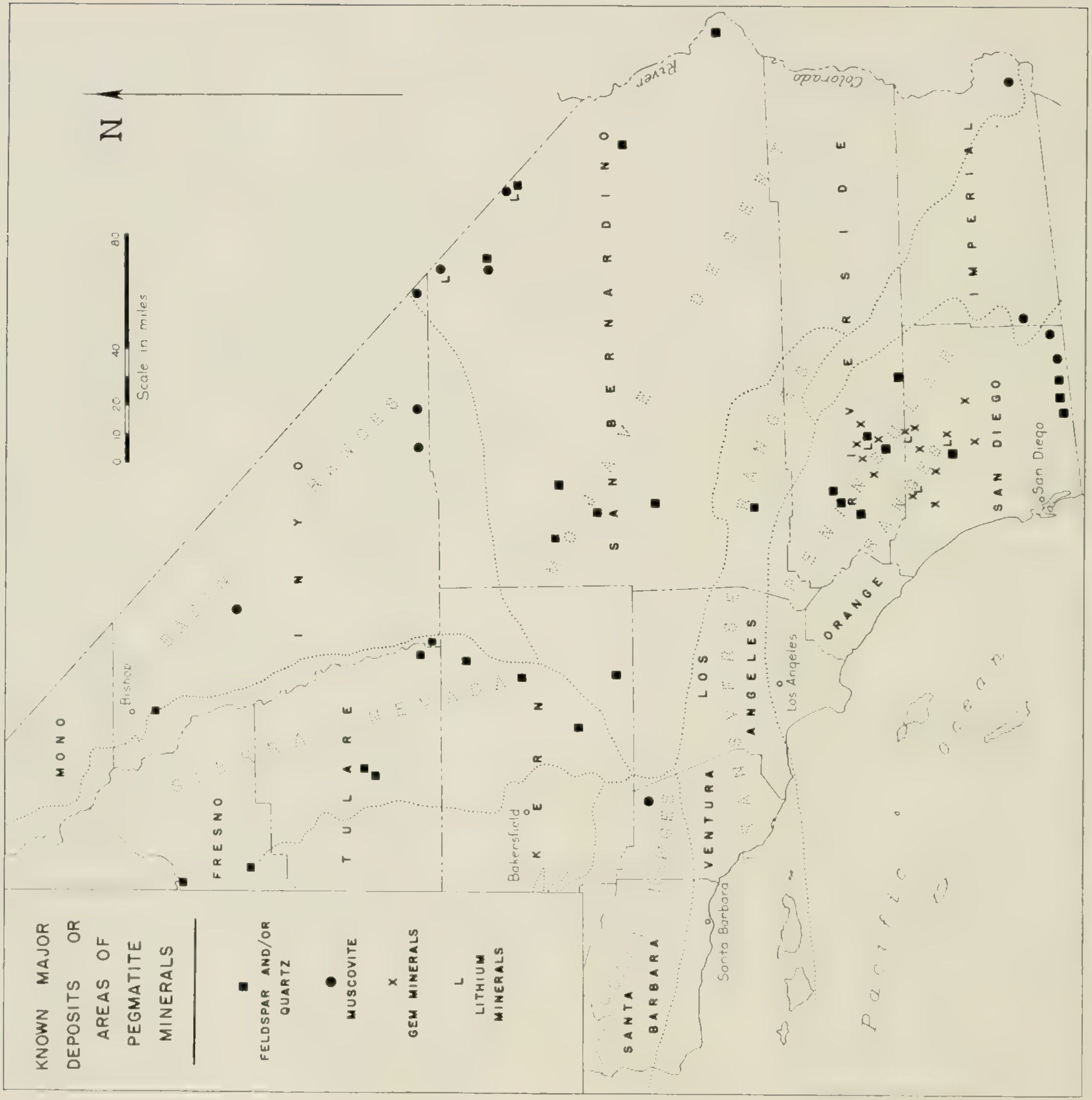

FIGURE 1. Index map of southern California, showing natural provinces and major pegmatite areas.

Table 1. Distribution and occurrence of pegmatites in southern California.

Province	General nature of pegmatite bodies	General composition of pegmatite bodies	Age of pegmatite	General abundance of pegmatite bodies
Sierra Nevada	Small to large dikes, sills, and pod-like masses	Tonalitic to granitic	Jurassic?	Sparse; abundant in only a few areas
	Very small stringers and pod-like masses in igneous rocks	Gabbroic	Jurassic?	Rare
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Tonalitic to granitic	Jurassic?	Abundant
Basin Ranges	Small to large dikes, sills, and pod-like masses	Mainly granitic	Pre-Cambrian	Sparse to locally abundant
	Small to moderately large dikes and pod-like masses	Mainly monzonitic to granitic	Mesozoic	Sparse to very rare
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Tonalitic to granitic	Mainly pre-Cambrian	Sparse; abundant in only a few areas
Mojave Desert	Small to large dikes, sills, and pod-like masses	Mainly granitic*	Pre-Cambrian	Sparse to locally abundant
	Small to moderately large dikes and pod-like masses	Mainly monzonitic to granitic	Mesozoic	Sparse to very rare
	Numerous small, irregular segregations in igneous rocks	Mainly granitic; some gabbroic	Pre-Cambrian and Mesozoic	Abundant in a few areas; very rare elsewhere
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Tonalitic to granitic	Mainly pre-Cambrian	Sparse; abundant in only a few cases
Transverse Ranges	Small dikes, sills, and pod-like masses	Tonalitic to granitic	Cretaceous or older	Sparse to moderately abundant
	Very small stringers and pod-like masses	Dioritic to gabbroic	Cretaceous or older	Abundant in a few areas; absent elsewhere
	Numerous small, irregular masses in *lit-par-lit* gneisses and other hybrid rocks	Dioritic to granitic	Cretaceous or older	Rare to locally abundant

Table 1. Distribution and occurrence of pegmatites in southern California—Continued.

Province	General nature of pegmatite bodies	General composition of pegmatite bodies	Age of pegmatite	General abundance of pegmatite bodies
Peninsular Ranges	Relatively continuous dikes and elongate pod-like masses	Mainly granitic†	Cretaceous	Very abundant as swarms in many well-defined areas; sparse elsewhere
	Small to moderately large dikes and pod-like masses	Tonalitic to quartz-monzonitic	Cretaceous and older	Sparse to very abundant
	Very small stringers and pod-like masses	Dioritic to gabbroic	Cretaceous	Locally abundant; absent elsewhere
	Numerous small, irregular masses, swarms, and stockworks in igneous, metamorphic, and hybrid rocks	Tonalitic to granitic	Cretaceous and older	Rare to locally abundant

* Includes a few bodies of lithium-bearing pegmatite.
† Includes numerous bodies of lithium-bearing pegmatite.

muscovite and biotite. Some of the potash feldspar contains graphic intergrowths of quartz. Minor amounts of garnet, tourmaline, magnetite, apatite, beryl, sphene, chlorite, epidote, and calcite are present locally.

The major minerals generally form anhedral to subhedral crystals that are ½ inch to 6 inches in maximum dimension. Most of the gabbroic pegmatites are uniform aggregates of such crystals, but in others the minerals show a distinct zonal distribution with respect to the walls of the containing body. This is in every way similar to the zoning described for granitic pegmatites by Cameron, et al. (1949). In general the pyroxene is near the walls, the hornblende is nearer the central part of the body, and the plagioclase is more widely distributed (fig. 3). Quartz and alkali feldspars, where present, are centrally disposed.

A similar zonal structure appears in most of the less basic segregation masses, and typical wall-to-center sequences include oligoclase—perthite—quartz, graphic granite—perthite—quartz (fig. 4), and oligoclase—graphic granite—perthite—muscovite and sodic albite—quartz.

Many of the segregation masses appear to have been formed in place, and they probably represent local concentrations of mineralizer-rich fluids that were developed during the end stages of crystallization of the enclosing igneous rock. Others evidently were injected

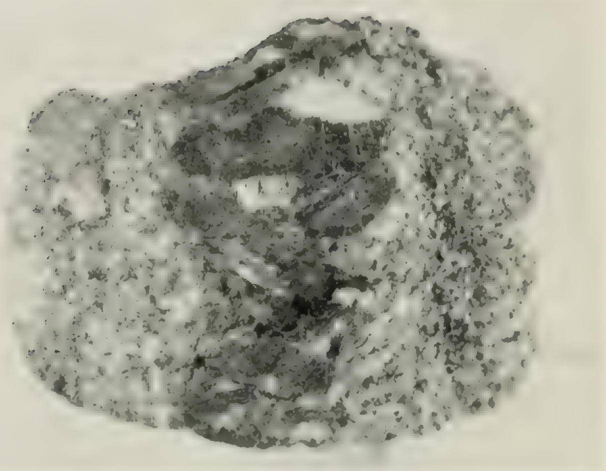

FIGURE 2. Three-inch stringer of hornblende-rich pegmatite in medium-grained gabbro, western San Gabriel Mountains.

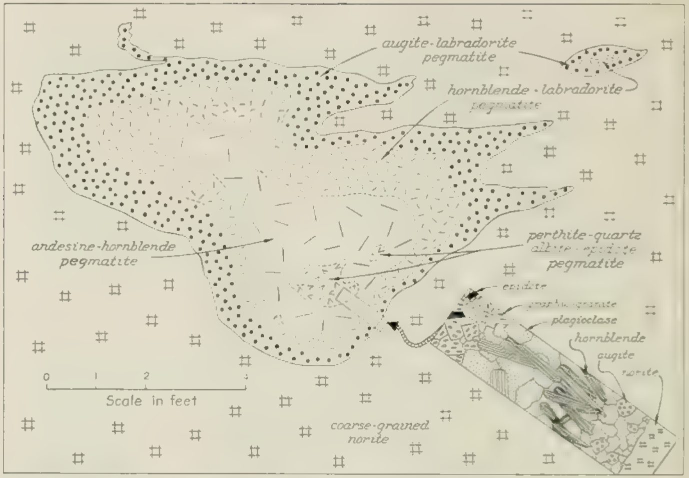

FIGURE 3. Pod-like mass of gabbroic pegmatite in coarse-grained norite, western San Gabriel Mountains.

into solid or nearly solid rock, and perhaps were derived from pockets of fluid that had formed elsewhere in the crystallizing intrusive mass. A variety of these auto-injection features has been described by F. S. Miller (1938, pp. 1220-1222, 1230) from gabbroic rocks of the Peninsular Range province. In no occurrences do the pegmatitic fluids appear to have moved for great distances from their sources.

In the gabbroic complex of the western San Gabriel Mountains, both anorthosite and norite are extremely coarse grained (see Higgs, Contribution 8, this chapter), and hence might be regarded as special varieties of pegmatite. These rocks form gigantic segregation masses, but no complete gradations in size are known between these masses and the small ones described above.

Most of the segregation masses of pegmatite in southern California appear to be genetic associates of Mesozoic igneous rocks, especially in the western parts of the region. Farther east, in the Mojave Desert and Basin-Range provinces, many of the pegmatite-bearing intrusives are pre-Cambrian in age.

PEGMATITE COMPLEXES AND HYBRID ROCKS

Pegmatite complexes, consisting in general of numerous small, irregular masses (fig. 5), are significant parts of the older crystalline rocks that form the so-called "basement complex" of many areas in southern California. They occur, for example, in the pre-

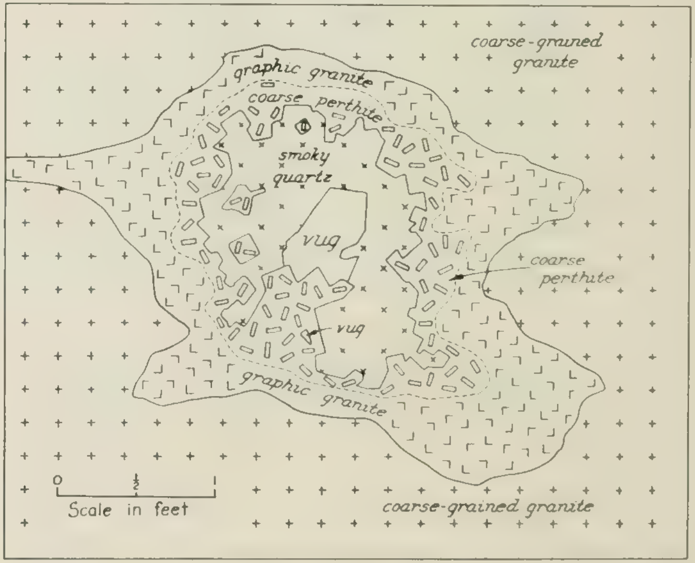

FIGURE 4. Pod-like mass of granitic pegmatite in coarse-grained granite, Whipple Mountains.

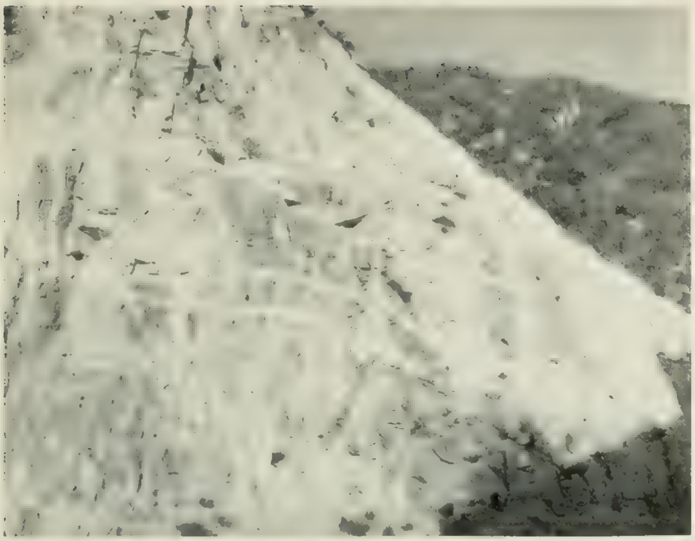

FIGURE 5. Typical complex of granodiorite pegmatite in hybrid gneiss, western San Gabriel Mountains.

batholithic rocks of the Peninsular Ranges and the Sierra Nevada, in the metamorphic rocks of the San Gabriel and San Bernardino Mountains, and in the early pre-Cambrian rocks of several desert ranges in the southeastern part of the State. In addition, they appear as parts of hybrid rocks and pegmatitized zones at and near the margins of many bodies of intrusive rocks. These contact complexes are chiefly of Mesozoic age in southwestern California, but both pre-Cambrian and Mesozoic ages are represented in areas farther east and northeast.

Though mentioned repeatedly in descriptions of crystalline rocks in southern California (for example, W. J. Miller, 1946), the pegmatite complexes have not been described in detail. They generally are referred to as groups of subparallel, anastomosing, or scattered small pegmatites, and all too often are dismissed as complicating elements in rocks that already seem too complex for interpretation by ordinary methods of study. The few detailed observations thus far made suggest that different pegmatites in some of these complexes were injected into, or were formed within, the host rocks at different times, and that the age differences commonly are reflected by differences in composition (fig. 6). The pegmatites also show significant relations to episodes of deformation, recrystallization, and reconstitution of the host rock, and further detailed study of such occurrences might well provide valuable information concerning the development of the rock as a whole.

Most of the pegmatite complexes are mineralogically simple, and consist of quartz, plagioclase, and potash feldspar, with or without micas and accessory constituents. In gross composition they range from tonalitic to granitic, and most are in the general granodioritic field. Many individual pegmatites in the complexes appear to be internally homogeneous, whereas others, especially the largest and most bulbous ones, show well-developed zonal structure like that described for the discrete pegmatites farther on.

Many of the pegmatite complexes are demonstrably intrusive into the containing rocks, whereas others just as clearly were developed in place by replacement of the host rock. Most appear to have been formed by some combination of the two general processes, but the quantitative relations are not easily determined, especially where the pegmatites form parts of lit-par-lit gneisses and other hybrid rocks. Further, it is evident that various complexes differ from one another in age, in conditions of emplacement, and in source of the pegmatite material. Much more study is needed before the problems can be properly defined, let alone solved!

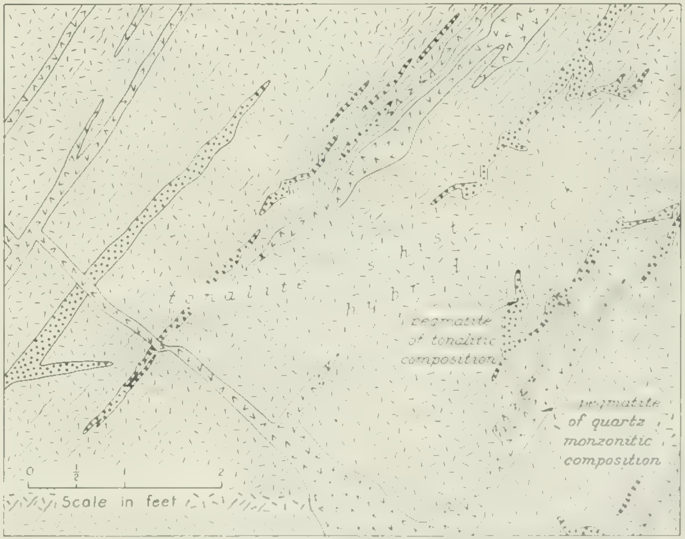
tonalite
hybrid schist
pegmatite of tonalitic composition
pegmatite of quartz monzonitic composition
0
½
1
2
Scale in feet

FIGURE 6. Pegmatite complex in tonalite-schist hybrid rock, near Escondido. Pegmatites of two different ages are represented.

DISCRETE PEGMATITE BODIES

Distribution and Occurrence. The discrete pegmatite bodies in southern California appear as dikes, sills, lenses, and masses of bulbous or highly irregular form. They are widely distributed in the Sierra Nevada, in the Basin-Range province to the east, in the Mojave Desert region, and in the Transverse Ranges and Peninsular Ranges in the southwestern part of the State (fig. 1).

As noted in table 1, these individual masses are particularly abundant in the Peninsular Range province, where most of them are genetically related to rocks of the great composite batholith of southern California (see Larsen, Contribution 3, this chapter). Pegmatites of tonalitic, granodioritic, and quartz-monzonitic composition are closely associated with stocks and other large plutons of similar respective compositions, and also appear in septa, screens, and larger masses of pre-batholithic metamorphic rocks. Somewhat younger pegmatites of granitic composition also are genetically related to the batholith, and occur mainly as subparallel dikes in certain of the gabbroic and tonalitic plutons. These include numerous gem- and lithium-bearing dikes. A few other pegmatites, mostly of granodioritic and quartz monzonitic composition, appear to antedate rocks of the batholith.

On the basis of their geologic relations, the pegmatites of the southern California batholith probably are middle or late Cretaceous in age (Jahns and Wright, 1951, pp. 18, 44). Isotopic analyses of lepidolite from the Stewart dike, at Pala, suggest ages ranging from about 110 million years (Ahrens, 1949, p. 250) to 147 ± 5 million years (Davis and Aldrich, 1953, p. 380), which would indicate a range from middle Cretaceous to middle Jurassic. An age of 100 million years, based on analyses of clean zircon concentrates, has been calculated for a tonalite (Larsen, et al., 1952) that represents the batholith. This tonalite is older than most of the pegmatites.

Individual masses of pegmatite also are abundant in parts of the southern Sierra Nevada, where they appear in plutons of the Sierra Nevada batholith and in older masses of schist, quartzite, and other metamorphic rocks. The batholith rocks are commonly regarded as Jurassic in age, and these pegmatites are therefore tentatively assigned to this period (see table 1).

Dikes, sills, and other bodies of pegmatite also are present in the Transverse Ranges, and are locally abundant in the San Gabriel, San Bernardino, and Little San Bernardino Mountains. Few of them are as large as many of the pegmatites in the region to the south and east, but they show the same general ranges in composition. Some of them may be as young as Cretaceous, but it is quite possible that many of them are Jurassic or older.

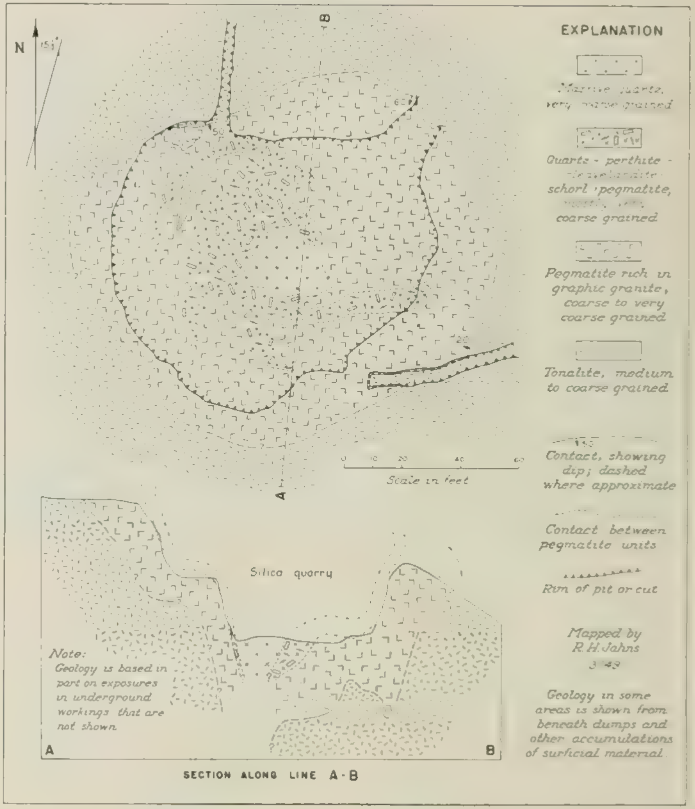
N
B
A
Silica quarry
Scale in feet
Note:
Geology is based in part on exposures in underground workings that are not shown.
A
B
SECTION ALONG LINE A-B
EXPLANATION
Massive quartz, very coarse grained
Quartz-perthite-cleavelandite-schorl pegmatite, mostly very coarse grained
Pegmatite rich in graphic granite, coarse to very coarse grained
Tonalite, medium to coarse grained
Contact, showing dip; dashed where approximate
Contact between pegmatite units
Rim of pit or cut
Mapped by R.H. Jahns 3-49
Geology in some areas is shown from beneath dumps and other accumulations of surficial material

FIGURE 7. Geologic sketch map and cross section of the Southern Pacific pegmatite, near Nuevo in western Riverside County.

Although crystalline rocks are well represented in the Basin-Range and Mojave Desert provinces of southeastern California, remarkably few pegmatites are present in these large areas (fig. 1). Scattered occurrences are known from the Inyo Mountains, the Panamint Range, the Amargosa Range, the New York Mountains, the Whipple Mountains, the Granite Mountains, and many other ranges and buttes in the region, but still other broad terranes of igneous and metamorphic rocks appear to be virtually barren of pegmatites. Among the bodies of pegmatite that have been observed, many are probably of Mesozoic age, especially in the western parts of the

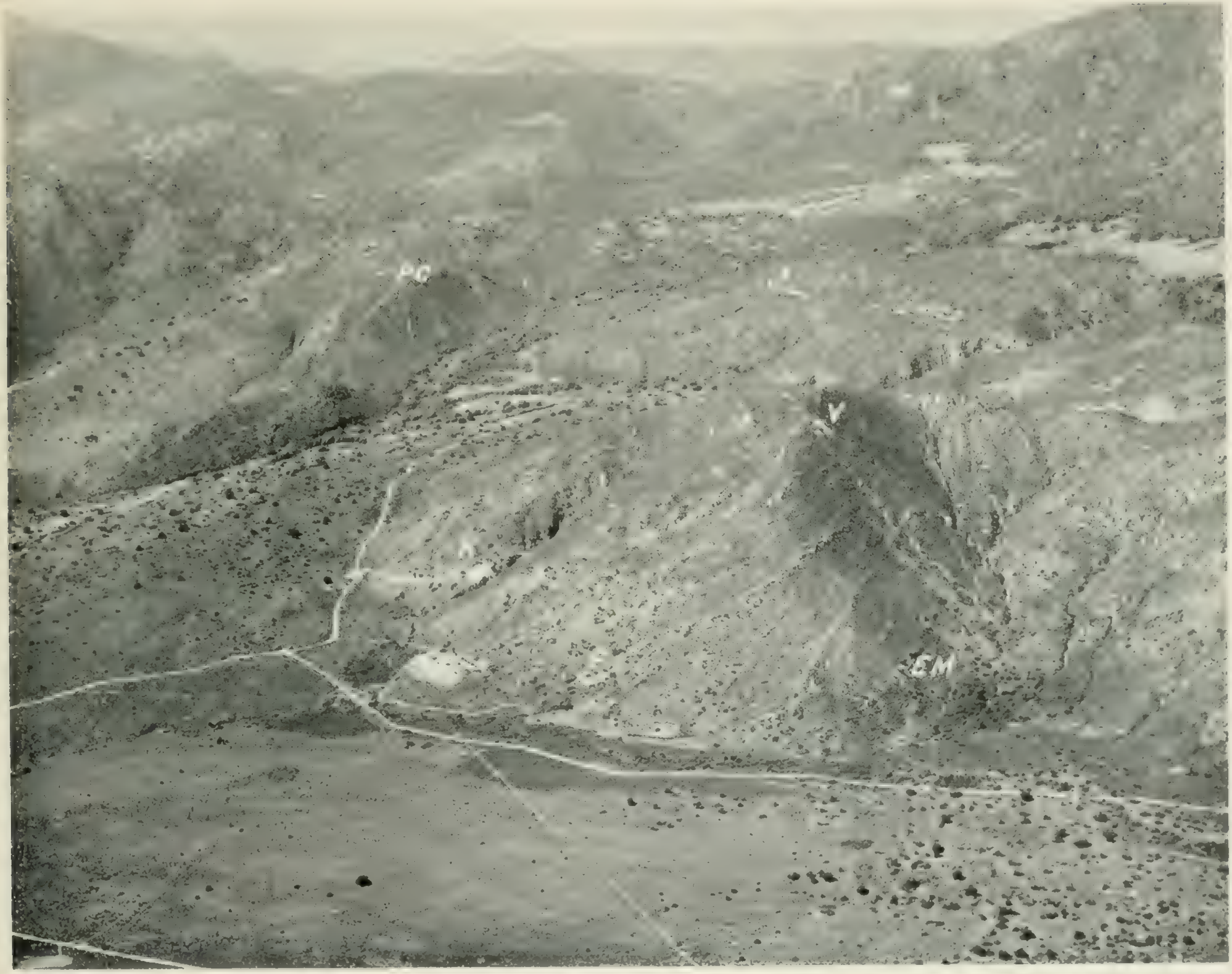

FIGURE 8. Aerial view north-northwest over a part of the Pala district, San Diego County. Subparallel dikes of gem-bearing pegmatite form rib-like outcrops on Hiriart Mountain, in foreground, and on Little Chief Mountain, immediately beyond wash in foreground at left. Gem mines in the view include the Katerina (K), Vanderburg (V), El Molino (EM), Fargo (F), and Pala Chief (PC). Elsinore fault zone at upper right. *Pacific Air Industries photo.*

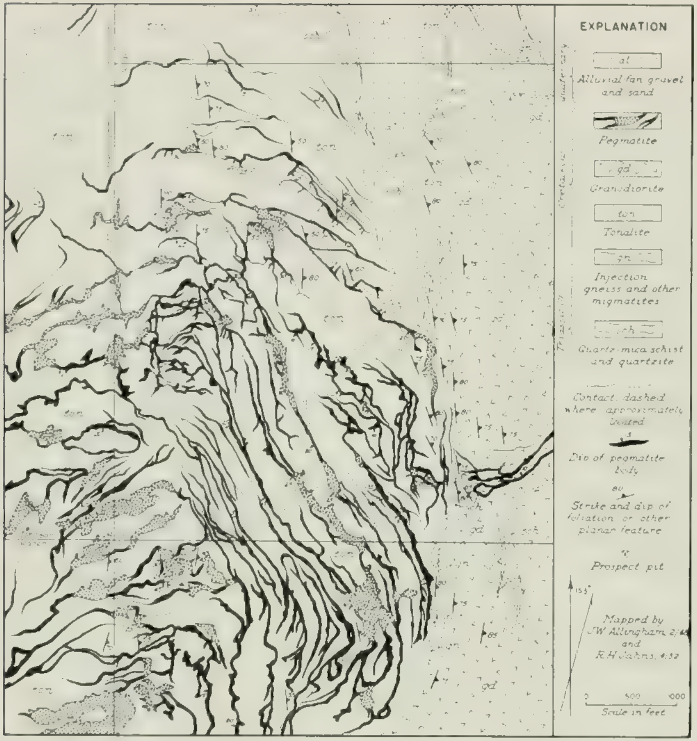
EXPLANATION
al
Alluvial fan gravel and sand
Quaternary
Pegmatite
gd
Granodiorite
ton
Tonalite
Cretaceous
gn
Injection gneiss and other migmatites
sch
Quartz-mica schist and quartzite
Triassic(?)
Contact, dashed where approximately located
Dip of pegmatite body
80
Strike and dip of foliation or other planar feature
Prospect pit
15½°
Mapped by J.W. Allingham, 2/48 and R.H. Jahns, 4/52
0 500 1000
Scale in feet
gd
ton
sch

FIGURE 9. Swarm of pegmatite dikes on Rincon Mountain, San Diego County.

region. Most of the remainder are pre-Cambrian in age, and some of those in the extreme northeastern part of San Bernardino County and the southeastern part of Inyo County may represent the northwestern edge of the so-called Arizona pegmatite belt, which embraces a large number of pre-Cambrian pegmatites in west-central Arizona.

Structural Features. The discrete pegmatites in southern California are highly variable in general form, attitude, and size, and do not differ markedly in these features from pegmatite bodies in many other parts of the world. Most are a few feet to about 500 feet in maximum dimension, and are moderately thick with respect to their length and width (fig. 7). Discordant bodies are predominant, and even the few that are concordant transect the country-rock structure in detail. The pegmatite-wallrock contacts generally are sharp, but in several occurrences they are gradational over distances of a few inches.

Noteworthy exceptions to some of the above generalizations are provided by most of the granitic pegmatites of the Peninsular Range province, and by a few of those in the southern Sierra Nevada. These are dikes with unusually large along-strike and down-dip dimensions relative to their thickness. They range in length from a few feet to nearly a mile, and are slightly less than 10 feet in average thickness. In most districts they are very uniform in attitude, and have moderate to gentle dips. They commonly appear as swarms, in which the individual dikes are essentially parallel to one another but tend to branch and join in detail (figs. 8, 9).

These thin and remarkably continuous dikes evidently were emplaced along subparallel fractures that are best developed in plutons of gabbroic and tonalitic rocks. The fractures are independent of schistosity, foliation, lineation, and primary flow layering in these rocks, and are not related systematically to the walls of individual plutons. They are thought to have been formed as tensional features during the end stages of cooling in the southern California and Sierra Nevada batholiths (Jahns and Wright, 1951, p. 18).

Many of the discrete pegmatites, regardless of their general form, appear to be essentially homogeneous internally, in that they are simple aggregates of quartz and feldspars, with or without micas and accessory minerals. Many others, in contrast, show a systematic internal arrangement of their constituent minerals, which ordinarily appears as a well-defined zonal structure (Cameron, et al., 1949; Jahns and Wright, 1951; Hanley, 1951). The pattern of zoning is remarkably consistent from one pegmatite body to another, and even from one pegmatite district to another. Each zone, which can be distinguished from the immediately adjacent zone on the basis of differences in mineralogy or texture, reflects to some degree the shape and size of the containing pegmatite body. The zonal structure in some pegmatite bodies is complicated by younger fracture fillings and replacement masses of closely related pegmatite, and locally by younger pegmatite dikes and sills that commonly are also zoned (fig. 10).

Composition and Texture. The gross composition of the discrete pegmatites in southern California ranges from tonalitic to granitic. Gabbroic pegmatites are by no means rare, but most of these seem best classified as segregation masses.

Quartz, perthite (generally microcline with lenticular lamellae of albite), and sodic plagioclase are the dominant minerals, and commonly are accompanied by muscovite, biotite, apatite, beryl, garnet, sulfide minerals, and tourmaline, either singly or in some combination. Rarer accessory constituents include bismuth minerals, cas-

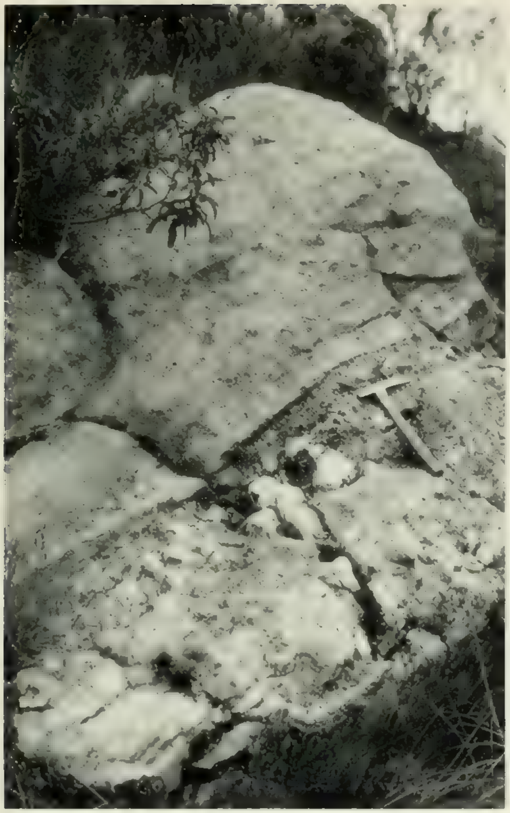

FIGURE 10. Composite pegmatite mass, Pala district, San Diego County. Three-foot sill of coarse-grained pegmatite is flanked by older, much finer-grained pegmatite. Note the sharp contact above hammer head. The margins of the sill are fine-grained quartz-albite-perthite pegmatite with muscovite, garnet, and schorl, and the inner parts consist mainly of coarse-grained graphic granite and quartz.

siterite, columbite-tantalite, epidote, microlite, monazite, spinel, topaz, and triplite (Murdoch and Webb, 1948, 1952; Jahns and Wright, 1951). Zeolites and clay minerals are widespread, but rarely are abundant. Lithium minerals are locally abundant in granitic pegmatites of the Peninsular Range province, and are present in a few pegmatites in the eastern Mojave Desert region.

The pegmatites that show no pronounced zonal structure generally are medium to coarse grained, and contain no marked concentrations of the less common minerals. Minor amounts of apatite, beryl, garnet, and other accessory minerals are disseminated through some of these rocks.

The outer parts of the zoned pegmatites generally are granitoid in texture, and are fine- to coarse-grained aggregates of feldspars and quartz, with or without other minerals. The inner zones, in contrast, are essentially monomineralic or consist of two or more minerals in coarse- to giant-textured aggregates (figs. 10, 11). Some of the crystals are truly enormous, and have dimensions measured in feet or even in tens of feet.

Perthite, much of it graphically intergrown with quartz, is abundant near the walls of many pegmatites, but where both plagioclase and potash feldspar are present in a given body, the plagioclase ordinarily lies nearer the walls. A noteworthy exception is the cleavelandite variety of albite, which has a wider distribution and is a common constituent of fracture fillings and replacement bodies. Quartz and potash feldspar are the most abundant minerals of the inner zones (figs. 7, 10), and the quartz is accompanied by spodumene and lepidolite in most of the lithium-rich pegmatites.

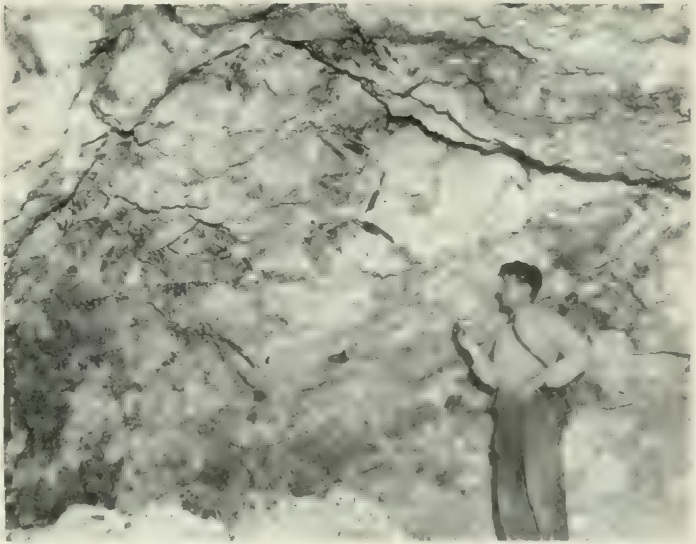

FIGURE 11. Very coarse-grained perthite and quartz, with large prisms of schorl. Perthite crystals are fringed with aggregates of muscovite and albite. Stewart mine, San Diego County.

The distribution of the less abundant minerals is highly irregular in detail, but does follow broadly consistent patterns. A given mineral, for example, commonly is restricted to a zone or other lithologic unit that is quite distinct from adjacent units in the containing pegmatite body. Where the mineral occurs in more than one unit in the body, it generally shows consistent differences in composition and physical properties from one unit to the next. These features have been discussed in detail elsewhere (for example, Cameron, et al., 1949), and need no further review here.

Masses of fine-grained rock that is essentially quartz-albite-microcline aplite occur in some of the pegmatite bodies, and are by far most abundant in the dikes of granitic composition in the Peninsular Range province. They are most prominent in the footwall parts of these dikes, but also occur elsewhere. Some varieties of the aplite are distinctly layered, and the planar structure is accentuated in many occurrences by thin, subparallel layers that are rich in tiny crystals of garnet and/or schorl. This variety of aplite is known in several districts as "line rock" (fig. 12).

Origin. The discrete pegmatites appear to have been formed by injection of liquid material along fractures or other planes of weakness in the host rocks, in some occurrences accompanied by minor digestion of the older rocks. This is in sharp contrast to many of the pegmatite complexes already described, in which much of the pegmatite clearly was developed by replacement of the older rock. The intrusive origin of the discrete pegmatites is evidenced mainly by combinations of the following features:

1. The borders of most masses are sharp, and commonly can be traced across contacts between different types of country rock without change in attitude.
2. The pegmatite bodies themselves show no changes in composition or internal structure that can be correlated with differences in country-rock lithology, nor does the internal structure of these bodies reflect the detailed structure of the country rock.
3. Schist and other thinly foliated types of country rock commonly are crumpled or otherwise disturbed immediately adjacent to many pegmatite contacts.
4. The structure, mineralogy, and age relations of the units within the zoned pegmatites are not compatible with a process of development through replacement of country rock (Cameron, et al., 1949, pp. 97-106).

Following their emplacement, the discrete pegmatites appear to have crystallized from their walls inward, with much the same mineral sequence as in any ordinary plutonic or hypabyssal rock. The structure of the zoned pegmatites seems best attributed to fractional crystallization and incomplete reaction between successive crops of crystals and rest-liquid (Cameron, et al., 1949, pp. 97-106; Jahns, 1953, pp. 580-595), chiefly because of the remarkable consistencies in age relations and textural and compositional trends from one zone to another.

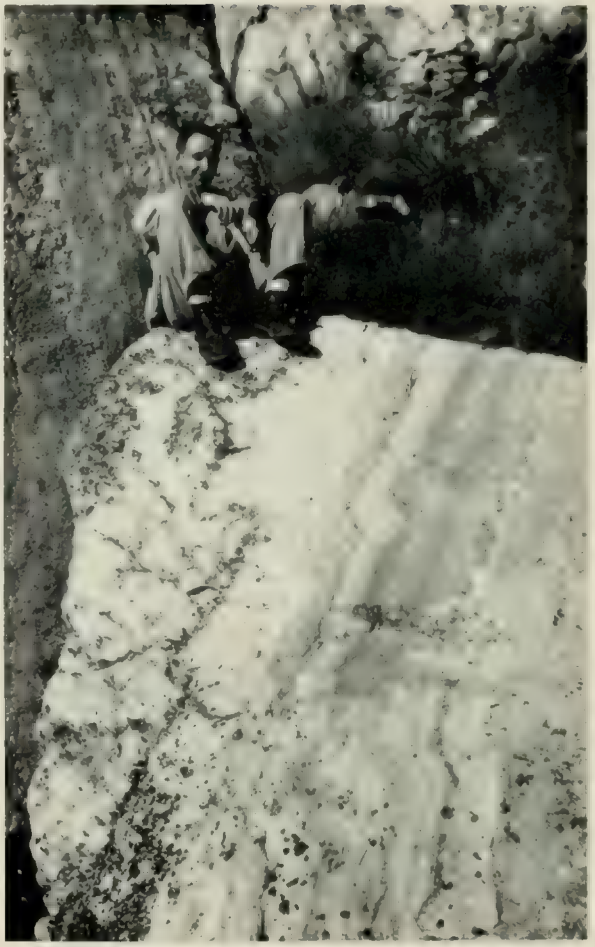

FIGURE 12. Sharply layered quartz-albite-garnet-microcline aplite (line rock) in contact with very coarse-grained quartz-rich pegmatite, near Pala, San Diego County.

Complications in the development of many of the pegmatites, especially during the end stages, are evidenced by widespread replacement features. In particular, much albite, muscovite, lepidolite, and quartz appears to have been formed in part by replacement of other pegmatite minerals, and evidences of corrosion and replacement are especially striking in the inner, pocket-bearing parts of many of the gem-bearing pegmatites. The total amount of replacement material rarely is large relative to the pegmatite body as a whole, but it may be moderately large in a few of the mineralogically complex bodies. Much of the replacement can be explained in terms of deuteric action during the intermediate and end stages of crystallization with a given mass of pegmatite.

The origin of the aplitic rocks within many of the pegmatite bodies is less clear. This fine-grained material has been variously interpreted as an early product of simple crystallization from a hydrous magma (Waring, 1905, p. 366), as an early, probably primary aplite, in some of which a rhythmic replacement yielded line rock and other layered varieties (Merriam, 1946, pp. 242-243), and as a much later result of replacement of pre-existing graphic granite by soda-rich solutions (Schaller, 1925, pp. 274-277). Evidence now at hand does not warrant a single definite conclusion, although it is clear that the aplitic rocks are integral parts of the pegmatite bodies in which they occur, and that some of these rocks show impressive evidence of mineral replacements.

GEOCHEMICAL FEATURES OF THE PEGMATITES

In general, the segregation pegmatites and the discrete pegmatites were formed from fluids that traveled varying distances from their sources, and can be regarded as late-stage products of magmatic differentiation. As such, they not only reflect the gross composition of larger igneous masses with which they are genetically associated, but also contain concentrations of rare elements that were present in the original magmas. Thus they provide samples of various magmas in the region—samples in which both major and minor constituents are relatively easy to recognize and study. Unfortunately, some of the pegmatite fluids seem to have moved such great distances from their sources that no genetically related rocks are exposed nearby. Certainly this appears to be the case with the granitic pegmatites of the Peninsular Range province.

Nearly all of the pegmatite bodies, including those of great mineralogic and structural complexity, are astonishingly similar to ordinary igneous rocks in gross composition. Even those with prominent masses of quartz rarely contain unusually high percentages of SiO_2, in terms of their entire bulk. Similarly, the percentages of alumina, lime, and the alkalies are in the normal ranges, and only iron is present in consistently low concentrations.

The minor constituents show some interesting trends. On the basis of mineralogic and chemical studies thus far made on the pegmatites of the Peninsular Range province, the magmas of the southern California batholith appear to have contained notable concentrations of boron, relative to magmas in other parts of the southwestern United States. Tourmaline is both widespread and abundant, and axinite is an accessory constituent of numerous pegmatites that are flanked or surrounded by limestone. Barium and strontium also are unusually abundant, and are concentrated mainly in the alkali feldspars. Lithium, phosphorous, and rare-earth elements are prominent minor constituents of many dikes, and thorium is well represented in several of them. Beryllium, bismuth, cesium, fluorine, manganese, columbium (niobium), rubidium, tantalum, titanium, and tin also are present, but not in unusual concentrations. Conspicuously rare are uranium, vanadium, and zirconium.

These observations are in good agreement with the results of trace-element studies that have been made on the various non-pegmatitic rocks of the batholith (see Larsen, Contribution 3, this chapter), except for the case of lithium, which has a low concentration in these rocks relative to the average igneous rock. Perhaps the concentrations of this element in the Peninsular Range pegmatites, relative to the average pegmatite, in part reflect the great difficulty with which it can be fixed in the earlier crystallizing minerals of the non-pegmatitic rocks, thus resulting in a high partition factor for lithium in favor of pegmatite fluids that separated from crystallizing masses of these rocks.

The trends in minor-element distribution are less well known for pegmatites in other parts of southern California, but a few generalizations can be made. Many of the Mesozoic pegmatites contain notable concentrations of boron, phosphorous, rare-earth elements, and titanium, and some of them are relatively rich in thorium-bearing minerals, as well. Although uranium-bearing minerals are known from a few of the pegmatites (for example, Hewett and Glass, 1953; Neuerburg, 1954), this element appears to be present in concentrations far below the average for pegmatites in general.

The pre-Cambrian pegmatites, and especially those in the eastern parts of the Basin-Range and Mojave Desert regions, evidently represent an entirely different geochemical province. They are relatively poor in boron, but are remarkably rich in fluorine. Many also contain moderate concentrations of rare-earth elements and tungsten.

The distribution of quantitatively minor elements within the southern California pegmatites is typical of that for pegmatites in general. Some of these elements form minerals of their own, and others appear as guests in minerals that generally were developed at a late stage during crystallization of the containing pegmatite body. Thus beryllium forms beryl, bavenite, bertrandite, gadolinite, phenakite, and helvite; bismuth occurs as a sulfide, oxide, vanadate, and in several carbonate minerals; tantalum and columbium (niobium) form tantalite-columbite, microlite, pyrochlore, hatchettolite, and several other complex minerals; and the rare-earths appear in

*Table 2. Occurrence of commercially desirable minerals in the pegmatites of southern California.**

Mineral or commodity	Province or region				
	Sierra Nevada	Basin Ranges	Mojave Desert	Transverse Ranges	Peninsular Ranges
Coarse potash feldspar	Common	Common	Common	Rare	Common
Mixed soda and potash feldspars, coarse†	Common	Common	Common	Sparse	Sparse
Sheet muscovite	Rare	Sparse	Very rare	Very rare	None known
Scrap muscovite	Rare	Common	Sparse	Rare	Sparse
Commercial quartz†	Common	Common	Common	Rare	Common
Commercial beryl	Sparse	Sparse	Rare	Very rare	Rare
Commercial spodumene	None known	None known	Very rare	None known	Sparse
Lepidolite	Very rare	Very rare	Very rare	None known	Common
Tantalum-columbium minerals	Very rare	Rare	Very rare	None known	Rare
Rare-earth minerals	Very rare	Rare	Sparse	Very rare	Sparse
Gem minerals	Very rare	Very rare	Very rare	None known	Common

* The terms used in this table apply to the individual pegmatite bodies within a given province or region; for an appraisal of the general abundance of each mineral or commodity within such a province or region, the terms should be combined with the data in the right-hand column of table 1. The terms are intended to have commercial application as follows:

Common—major or widespread constituent of several pegmatites, or lesser constituent of many; commercially significant.

Sparse—major or widespread constituent of only one or two pegmatites, or moderately abundant in a few, or a minor constituent of many; of limited commercial significance.

Rare—minor constituent of a few pegmatites; of little commercial significance.

Very rare—known constituent of one or more pegmatites, but of mineralogic interest only.

† Rarely or never marketed because of geographic occurrence and/or low commercial demand.

monazite, allanite, euxenite, gadolinite, pyrochlore, samarskite, and xenotime. Cesium forms very rare pollucite, and is present as a guest element in much of the beryl. Fluorine forms fluorite in many of the pegmatites, and also is a widespread minor constituent of apatite, topaz, amblygonite, micas, and other minerals. Rubidium is a guest constituent of lepidolite and potash feldspar, and both strontium and barium appear in the alkali feldspars. Boron is mainly an essential constituent of the tourmaline and axinite.

ECONOMIC FEATURES OF THE PEGMATITES

Commercial operations in the pegmatites of southern California have yielded substantial amounts of quartz, feldspars, mica, lithium minerals, gem minerals, and other commodities, the total value of which probably exceeds 4 million dollars. Slightly more than half of this value is represented by the output of gem materials, consisting mainly of tourmaline, spodumene, beryl, topaz, garnet, and quartz. The geographic occurrence of these and other commercially desirable minerals in southern California is indicated in table 2.

The gem-bearing pegmatites of the Peninsular Range province have been mined intermittently since about 1890, but much of the easily recoverable material appears to have been worked out. Additional masses of gem-bearing ground are present in several districts, and detailed geologic studies have disclosed numerous structural and mineralogic features that should aid further prospecting and exploration; nevertheless, new concentrations of gem minerals undoubtedly will be more difficult and expensive to find than those already known and worked.

Feldspar has been mined from at least 40 large bodies of pegmatite in the eastern and southern parts of the Peninsular Range province, and from a few scattered occurrences in the Mojave Desert and Basin-Range regions. Production has amounted to about 150,000 tons, nearly all of which has consisted of very coarse-grained potash feldspar obtained from the inner parts of zoned pegmatite bodies (figs. 7, 13). Additional reserves of high-grade material are present, but commercial operations have been seriously limited by the distances of most deposits from centers of demand, as well as by keen competition from talc and other minerals, especially in the ceramic industry.

Small tonnages of pegmatite quartz have been obtained, chiefly for special ceramic uses, from several deposits in the Peninsular Range, Sierra Nevada, Basin-Range, and Mojave Desert provinces. The quartz ordinarily mined is very coarse grained and relatively pure, and commonly is associated with coarse potash feldspar in the central parts of large pegmatite bodies (figs. 7, 13). Demands for this material rarely are large.

No deposits of sheet muscovite are known from most pegmatite areas in southern California, and only a few small lots of this material have been obtained from the deposits that are sparsely scattered through the southeastern part of the State, and through parts of the Sierra Nevada and Transverse Range provinces. Mining for scrap mica has been more widespread, especially in the southeastern part of the Peninsular Range province, but production never has been large.

The Stewart mine, in San Diego County, yielded large tonnages of lepidolite, as well as some amblygonite and spodumene, during the period 1895-1928, and at one time was the largest domestic producer of lithium minerals. The two main ore bodies have been worked out, but additional concentrations of lepidolite and spodumene may be present elsewhere in this large pegmatite body. Small quantities of lithium minerals are known to occur in several other pegmatites

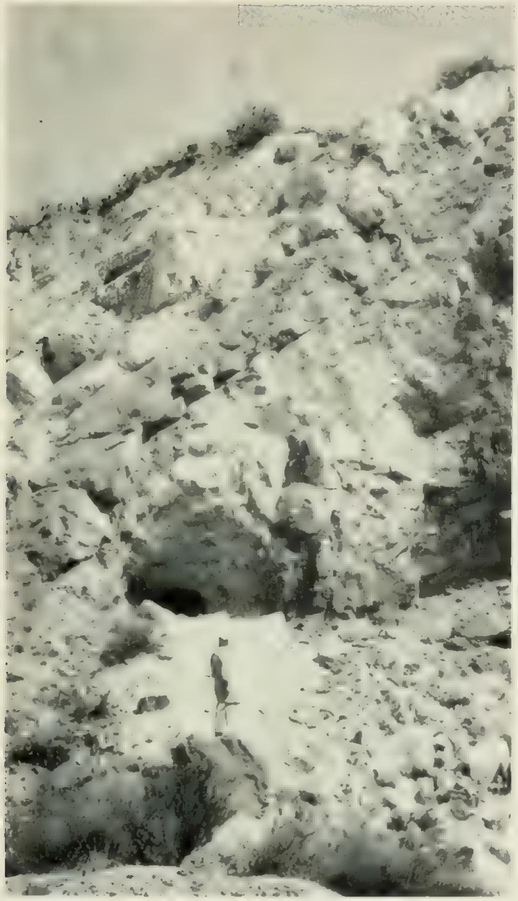

Figure 13. Very coarse-grained pegmatite, rich in quartz and perthite. Dark-colored rock is a septum of quartz-biotite schist. Houser Canyon feldspar quarry, San Diego County.

in the Peninsular Range province, as well as in the easternmost parts of the Mojave Desert and Basin-Range regions in the State.

The known pegmatitic occurrences of bismuth minerals, cassiterite, non-gem beryl, rare-earth minerals, tantalum-columbium minerals, and thorium minerals in southern California thus far have been of mineralogic interest only.

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6. CONTACT METAMORPHISM IN SOUTHERN CALIFORNIA[*]

BY IAN CAMPBELL[†]

General Features. A highly condensed introduction to "Contact metamorphism in southern California" is obviously not the place in which to indulge in semantic niceties nor to engage in terminological tussles, and thus the title is not intended to reflect a carefully delimited concept. Instead it is freely admitted that in some of the examples to be cited, such terms as "contact metasomatic," "pyrometasomatic," "optalic" or "thermal metamorphic," "hydrothermal," "pneumatolytic," and even "injection metamorphism" might be more precisely appropriate. Suffice it to say that "contact metamorphism" will be herein employed in its broader connotations.

There is an old adage which states that "it takes two to make a quarrel." Likewise, it takes two (rocks) to make a contact, and unless one of these rocks was at one time pretty hot, preferably indeed in the magmatic state, there is likely to be no contact metamorphism as such. With the concept of contact metamorphism thus reduced to these two essentials, an invaded rock and an invading magma, let us survey the southern California field.

In terms of rocks available for invasion, southern California presents a wide range: in age, from pre-Cambrian to Recent; and, in type, encompassing sandstones, shales, cherts, limestones, dolomites, graywackes, pyroclastics, conglomerates, the regionally metamorphosed equivalents of these rocks, and a considerable variety of igneous rocks. Details concerning "country rock" types will be found elsewhere in this volume.

The invading magmas likewise involve wide spans of time and of type. In the early pre-Cambrian ("Archean" of some writers) terranes, plutonic intrusives, largely granitic, have been recorded principally from the southeastern parts of the State. In the later pre-Cambrian ("Algonkian" of some writers), intrusive activity seems to have been largely confined to injection of diabasic sills, also in the southeastern parts of the State. The Paleozoic record is very fragmentary, but gives the impression that this era, if not wholly devoid of igneous activity, at least did not involve any very significant effects of such. The Triassic was a period of considerable volcanism, manifested more in the pyroclastic record than in other ways, and involving chiefly andesitic types. Then, probably in Upper Cretaceous time,[‡] came the invasion of the southern California batholith (Larsen, 1948) and its correlatives, e.g. the Cactus granite (Vaughan, 1922), some of which are found far to the east. In this, as in other major plutonic sequences throughout the State, rocks ranging from norite and gabbro through diorite, tonalite, granodiorite, and quartz monzonite (adamellite) to granite and alaskite are represented, with the sequence in most instances proceeding from the more mafic toward the more felsic types. Hewett (1948) has recognized late Laramide granitic intrusives in the southeastern portion of the State, and as dating methods improve, other occurrences may be assigned to this period, and to periods not now included in the record of igneous activity.

In Cenozoic time there was abundant igneous activity in southern California, but probably not until erosion has provided us with much deeper exposures will evidence of plutonic phases be found. Cenozoic activity is manifested chiefly in widespread volcanic phenomena, with basaltic, intermediate, and rhyolitic magmas involved. Even within the Quaternary there is a widespread record of both basaltic and rhyolitic effusions, as, for example, in Mono County (Putnam, 1938). Throughout the time scale, the great bulk of igneous activity has been confined to what are sometimes classed as the "calc-alkaline rocks." Ultramafic types are few and far between (these are much more abundant in northern California), and alkaline types are almost non-existent save for some relatively minor intrusions of nepheline syenite and associated types in the northern Panamint Range (McAllister, 1952), and the shonkinite recently recognized (Sharp and Pray, 1952) in connection with the bastnaesite deposits of the Mountain Pass area in San Bernardino County (see also Olson and Pray, Contribution 3, Chapter VIII).

In view of the diversity of both invaded and invading types, it might be anticipated that southern California would exhibit contact metamorphic types whose number would approximate the number of invaded types multiplied by the number of invading types. That no such tremendous number of metamorphic types actually exists might be explained in two ways. First, if we assume that metamorphism is purely thermal, then it matters little what the composition of the intrusive is; results will be a function only of its temperature, and of the physics and chemistry of the intruded rock. Second—and this is doubtless the commoner case—if we assume that thermal effects are in part transmitted and augmented by emanations associated with the intrusive, the major components of these emanations are likely to be such end-stage concentrates as H_2O and SiO_2, regardless of whether these stem from a gabbroic or a granitic magma. Thus with respect to the best known sequence in this region, that of the southern California batholith, Larsen (1948, p. 36) comments, "Both the thermal and hydrothermal contact metamorphism around the tonalite, gabbro, and peridotite are much alike, and they are similar to the metamorphism commonly found around granite and granodiorite."

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[‡] The dating of the "batholith of southern California" presents a problem not as yet fully solved. The intrusives of the Sierra Nevada to the north, with which the southern California batholith has been correlated by some investigators, have been rather closely dated by Hinds (1934) as probably late Jurassic. On the other hand, the intrusives of the Sierra San Pedro Martir in Baja California, with which the southern California batholith might better be correlated, have been shown by Woodford and Harriss (1938) to be Upper Cretaceous in age (see also Larsen, Contribution 3, this chapter).

In general it can be said that contact metamorphism is most extensively developed around granitic (granodiorite, quartz monzonite, and granite) intrusives of Mesozoic age. Earlier intrusives commonly invaded rocks that already had been regionally metamorphosed, and therefore were less likely to display effects of contact metamorphism. And contact metamorphism is most extensively developed in pelitic and impure calcareous country rocks, whereas arenites, meta-arenites, pure marbles, igneous rocks, and metamorphic rocks commonly show little or no contact effects other than local recrystallization.

Despite these simplifying considerations that are involved in this picture of contact metamorphism, southern California does not lack for a notable range of contact metamorphic types. Varieties are found that range from spotted (cordierite) slates (Hoots, 1931) that may be classed in the green schist facies, to diopside-plagioclase rocks (Durrell, 1940) that manifestly represent the intense conditions of metamorphism of the pyroxene-hornfels facies. Sillimanite schists (for example, Merriam, 1946) are widespread high-rank types in the region, although by no means all of the sillimanite can be ascribed to contact metamorphism.

The greater part of the contact metamorphism to be found in southern California appears mainly to confirm principles and examples already well documented from many other parts of the world, although some of the examples are particularly well exposed, either because of king-size road cuts or because of scanty desert vegetation. But California prides itself on providing superlatives and uniqueness! Granting that the majority of the contact metamorphic rocks display nothing out of the ordinary, there are nevertheless instances to which special attention might be called. The remaining discussion will cite briefly a number of such instances, several of which receive more extended discussion elsewhere in this volume.

Examples of Contact Metamorphism. Evidence of a superlative thermal punch packed by some California magmas is provided by a granodiorite locally vitrified by intrusion of a Pleistocene (?) basalt, near Bishop (Knopf, 1938). Here tridymite is found in a low-index glass formed by the melting down of quartz and alkali feldspar. And from near Carlsbad, in San Diego County, Larsen and Switzer (1939) record a large (40 by 50 feet) inclusion of tonalite that has been nearly half melted down to glass of rhyolitic composition by an intrusive plug of andesitic lava (figs. 1, 2). But the highest thermal effects undoubtedly are those represented by sand fulgurites near Indio, for which Rogers (1946) estimated temperatures of around 1800°C. Within the writer's broadly stated conception, the conversion, in these fulgurites, of quartz to lechatelierite and cristobalite, accompanied by fusion of biotite and of feldspar, is certainly contact (thermal) metamorphism, although admittedly of a very special (non-magmatic) type!

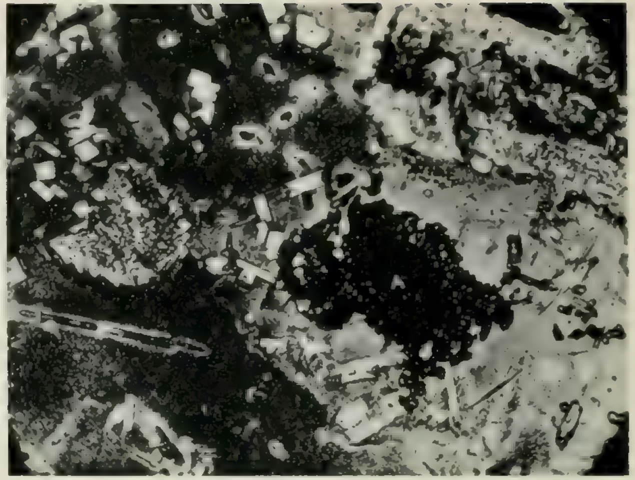

FIGURE 1. Fused inclusion, Calaveras quarry, San Diego County. Hornblende phenocryst altered to augite (A), glass (G) with swallow tail feldspar (F) phenocrysts. *Reproduced from Larsen and Switzer (1939), courtesy American Journal of Science.*

Other indications of thermal punch are less dramatic, but deserve mention. Sillimanite, considered by many as an index mineral of maximum metamorphic intensities, has been recorded from a number of widely separated localities (Murdoch and Webb, 1948, p. 273). Much of it may well be the result of regional metamorphism, but some is to be attributed to contact metamorphism. A much more unique indicator of the attainment of an advanced stage of meta-

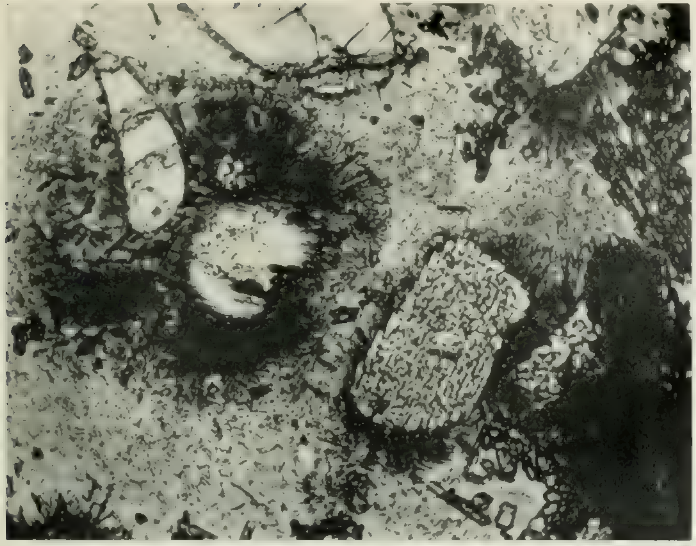

Figure 2. Fused inclusion, Calaveras quarry, San Diego County. Partially melted feldspar (F), showing manner in which solution progressed along cleavage directions. Glass (G) and quartz (Q). *Reproduced from Larsen and Switzer (1939), courtesy American Journal of Science.*

morphism is the mineral merwinite, which is present at Crestmore.* In the well-known Bowen (1940) series of 10 mineral indicators of progressive metamorphism of siliceous dolomites, merwinite stands ninth, with only larnite above it. If, as is now generally done, rankinite is added as an eleventh member of this list, merwinite is still only two from the top, and thus places the rock in which it occurs with the pyroxene-hornfels facies. Monticellite, lower (sixth) in the Bowen table, still represents an intensity stage of contact metamorphism not commonly reached. It is present at Crestmore, and also is found in the Ivanpah area (Schaller, 1935) far to the east. Predazzite, a rock representing the periclase stage of contact metamorphism, is somewhat of a rarity in the United States, but it has been reported (Rogers, 1918 and 1929; Woodford, et al., 1941) from three quarries in the vicinity of Riverside (City quarry, Crestmore quarry, and Jensen quarry), and from Lucerne Valley (Campbell, 1950).

Not only have southern California magmas carried, at times, exceptionally high thermal energy, but they have invaded rock types not commonly found in contact zones. For example, Miocene cherts and other high-silica beds of the Monterey formation in the Palos Verdes Hills develop, according to Bramlette (1946), narrow contact zones adjacent to dikes and sills of basalt. These zones are characterized by an increase in chalcedonic silica and by formation of ankerite. Durrell (1940) cites progressive recrystallization and sutured boundaries of quartz as the major effects where meta-cherts are present within contact zones of the southern Sierra Nevada intrusives. It is of interest to note, by way of providing a measure of the intensity factor, that sillimanite is locally formed in these meta-cherts.

Gypsum provides further evidence that monomineralic rocks seldom are greatly affected by contact metamorphism. In the Palen Mountains, Hoppin (quoted in Ver Planck, 1951) has mapped thick gypsum beds and associated sediments of uncertain but possibly Paleozoic age. These have been intruded by Jura-Cretaceous (?) quartz diorite, with resultant development of garnet skarns in the lime-silicate formation, but apparently with no recognizable effects on the gypsum. Hoppin does postulate that dehydration to anhydrite might have resulted, but that subsequent approach to the surface and to the zone of ground-water circulation may have rehydrated the formation to its earlier composition. Progressive effects of emanations from a quartz-diorite upon serpentine in the southern Sierra Nevada have been recognized by Macdonald (1941) as characterized by successive development of talc, talc and actinolite, actinolite, chlorite, and biotite.

One of the most unusual of southern California's contact metamorphic deposits is the andalusite mass in the northern Inyo Mountains, which for many years furnished ore for the Champion Spark Plug Company. Whether this notable concentration of highly aluminous minerals developed because of unusual composition of the country rock, or because of other factors, it is impossible now to say. Extensive alteration has so obscured the relationships as to leave certain important elements of the geology in doubt. Knopf (1917), who first called attention to the occurrence, postulated pneumatolytic metamorphism of a volcanic porphyry subsequent upon granitic intrusions. Kerr (1932) suggested that the host rock may have been an aluminous volcanic type, or possibly an aluminous sediment intercalated in a succession of trachytic flows, now largely schists, and that the metamorphism responsible for development of the andalusite was associated with intrusion of a porphyry of trachytic composition.

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* To what extent Crestmore, the most remarkable of all of California's mineral deposits in terms of number and rarity of mineral species, owes its exceptional features to contact metamorphism and to what extent these are to be attributed to more strictly hydrothermal effects, is discussed elsewhere in this chapter (Burnham, Contribution 7). Let it suffice to point out here that the bulk of the marmorization and of the lime-silicate zones at Crestmore are certainly contact metamorphic in origin; the rare, minor, and in part hydrous constituents (e.g., custerite, hillebrandite) are very probably of later, but related, hydrothermal development.

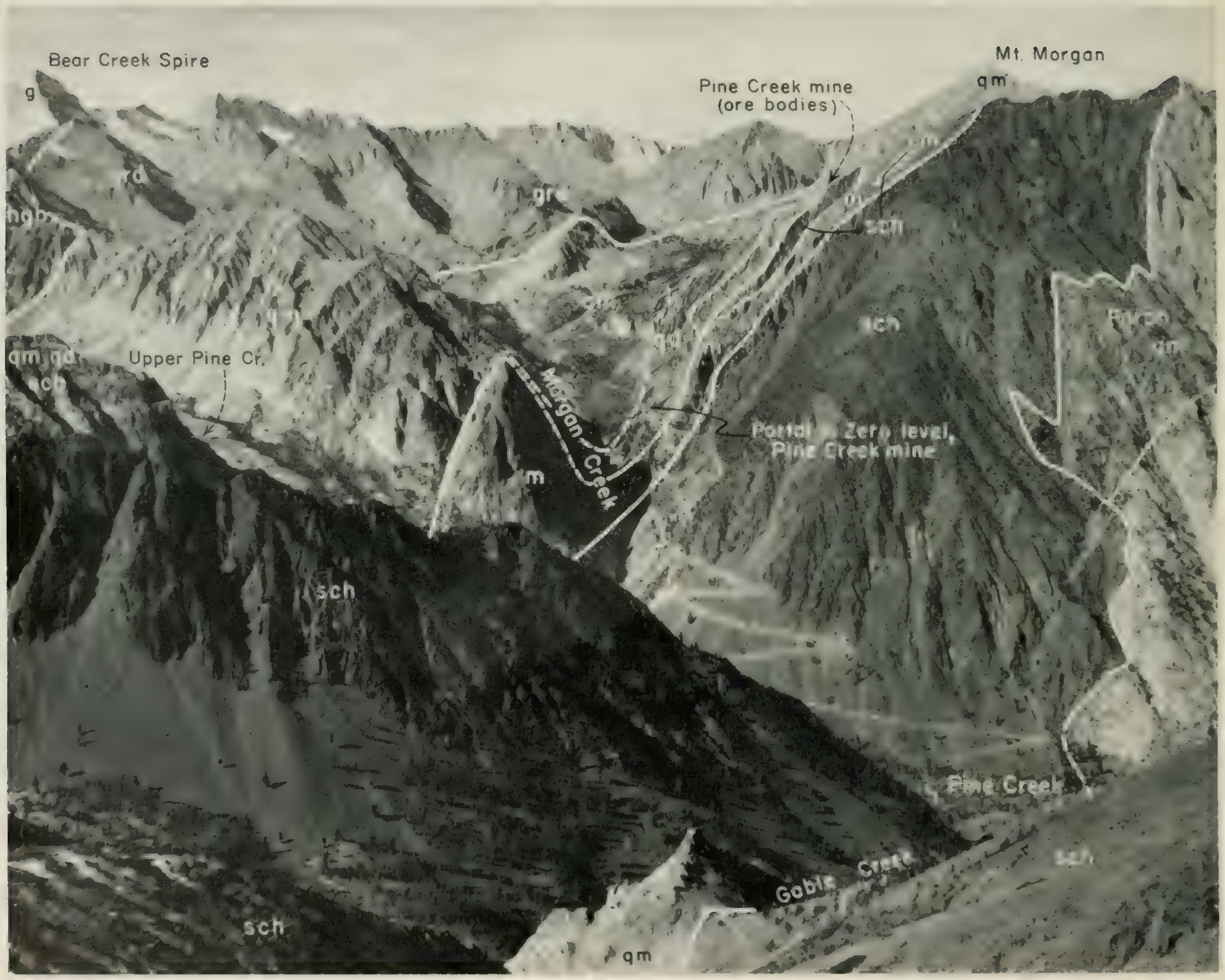

FIGURE 3. Pine Creek pendant in the vicinity of the Pine Creek mine of U. S. Vanadium Company, Inyo County. g, Orthoclase-albite granite; grd, granodiorite; hgb, hornblende gabbro; porph qm, quartz monzonite with large phenocrysts of orthoclase (probably correlative with Cathedral Peak granite of Yosemite Park); qd, mafic quartz diorite; qm, quartz monzonite; sch, schistose quartz rock; m, marble. *Photo and geology by Dwight Lemmon and Paul Bateman, U. S. Geological Survey.*

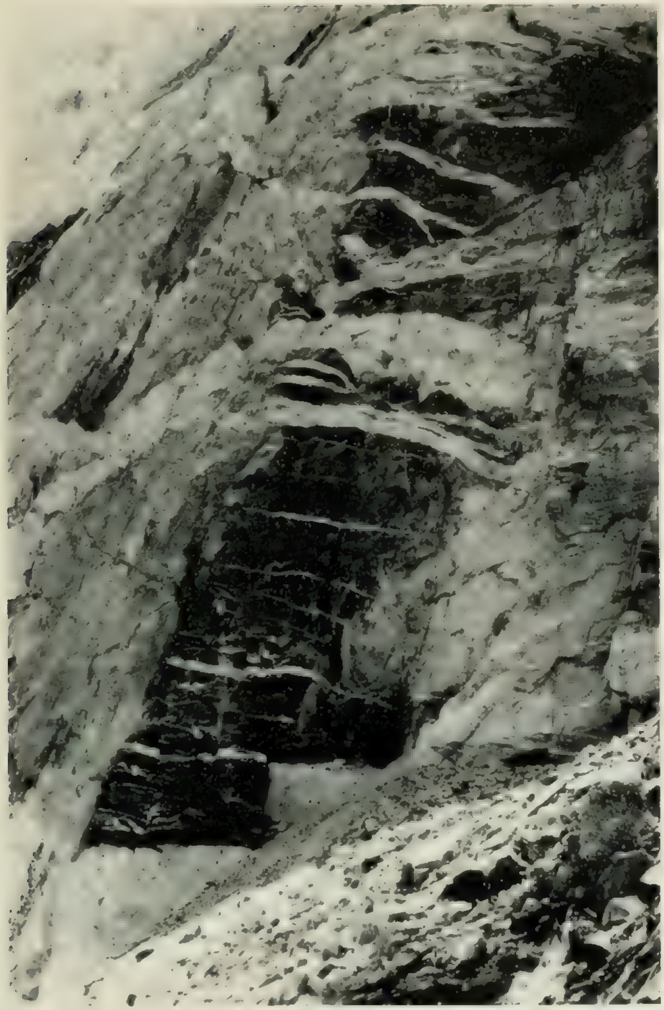

FIGURE 4. Tactite zone in cliff face (face showing is about 150 feet high) at Brownstone tungsten mine, Pine Creek Canyon, Inyo County. The dark material is garnet-pyroxene tactite. It is bounded on the right by quartz monzonite, and on the left by marble. All these are cut by gently dipping felsite dikes (lightest gray). *Photo courtesy Paul C. Bateman, U. S. Geological Survey.*

Later, Lemmon (1937) indicated that the andalusite occurs in a pre-Cambrian metaquartzite, and is a result of intrusion of late Jurassic granitic rocks associated with the Inyo batholith. At any rate, there is general agreement that the andalusite deposit resulted from igneous invasion, but whether large or small amounts of aluminum were supplied by the intrusive cannot be determined in advance of final decision as to the original composition of the host rock. The first stages of metamorphism are characterized principally by the development of corundum and andalusite. Later, and more particularly, hydrothermal stages resulted in formation of diaspore, pyrophyllite, muscovite, alunite, lazulite, and such rare minerals as augellite and woodhouseite.

Emanations are almost invariably involved in contact metamorphism, and it is from these that some of the State's most important economic mineral deposits have resulted. Certainly no summary of contact metamorphism in southern California would be complete without reference to the scheelite-bearing tactites (fig. 3) that through two world wars have yielded a very large share of our domestic output of tungsten. Economic and scientific interest first focussed upon these deposits during World War I, and in 1922 Hess and Larsen pointed out that the vast majority of them are present in the Great Basin region of California and Nevada, and that they are most commonly found in limestone country rocks associated with quartzose intrusives. Many early studies of these deposits have shown that their broad relationships are remarkably consistent, and this generalization has been confirmed by extensive and detailed mapping of tungsten deposits during the period of World War II.

In a typical contact-metamorphic deposit of scheelite, the zone immediately adjacent to and extending outward from the intrusive contact—in some places for tens, in others for hundreds, of feet—is the "tactite zone". It is commonly distinguished by colors darker than those of the adjoining rocks, and is characterized by development of such minerals as garnet, diopside, epidote, and idocrase. Scheelite ordinarily is most abundant in this zone, but is by no means confined to it. Molybdenite not uncommonly accompanies the scheelite, and pyrite, chalcopyrite, and magnetite are common and locally abundant accessories. The borders of the tactite zone are characteristically though not invariably sharp (fig. 4). The shapes of tactite bodies are notoriously irregular, and this irregularity has led to many difficulties in the economic and engineering development of these deposits.

Beyond the tactite zone, as traced away from the intrusive rock, is the "zone of light-colored silicates," which is characterized by such minerals as wollastonite and tremolite, and in rare instances by scheelite in commercial concentrations. This zone in turn passes

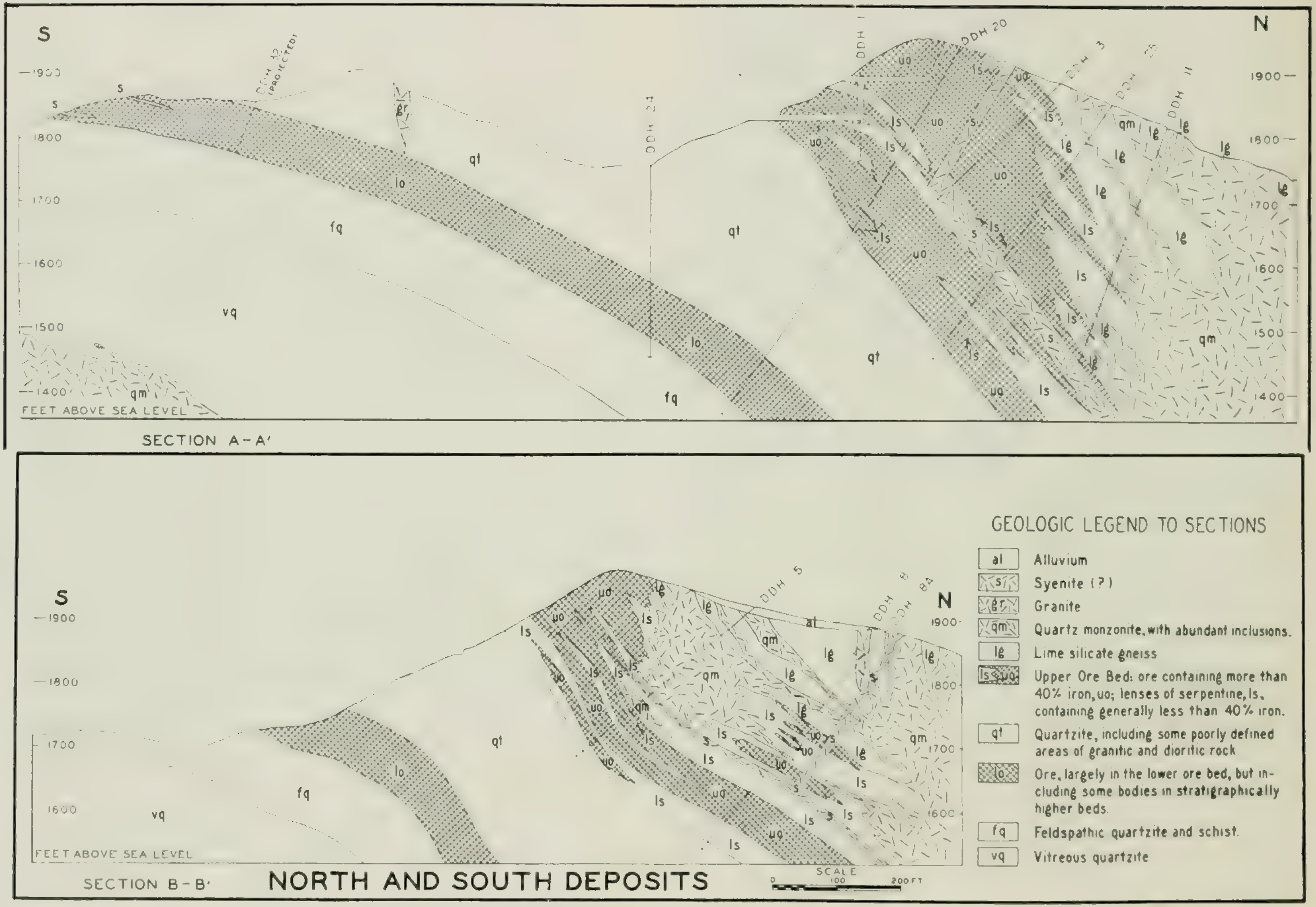
S
N
SECTION A – A′
SECTION B – B′
FEET ABOVE SEA LEVEL
1900
1800
1700
1600
1500
1400
DDH 32 (PROJECTED)
DDH 24
DDH 1
DDH 20
DDH 3
DDH 25
DDH 11
DDH 5
DDH 8
DDH 8A
s
gr
qt
lo
fq
vq
qm
uo
ls
lg
al
NORTH AND SOUTH DEPOSITS
SCALE
0
100
200 FT
GEOLOGIC LEGEND TO SECTIONS
al Alluvium
s Syenite (?)
gr Granite
qm Quartz monzonite, with abundant inclusions.
lg Lime silicate gneiss
ls uo Upper Ore Bed: ore containing more than 40% iron, uo; lenses of serpentine, ls, containing generally less than 40% iron.
qt Quartzite, including some poorly defined areas of granitic and dioritic rock
lo Ore, largely in the lower ore bed, but including some bodies in stratigraphically higher beds.
fq Feldspathic quartzite and schist.
vq Vitreous quartzite

FIGURE 5. Structure sections, showing the relationships of iron-ore bodies in the Eagle Mountains, Riverside County. Both the upper and lower bodies are shown in a single pattern, and all intrusive rocks are likewise shown in a single pattern. *Modified from Hadley, 1945.*

gradually outward into a marmorized zone, characterized by an absence of additive minerals, and in which the only contact effect is recrystallization of the calcite. This zonal pattern, with variations, is found in many parts of southern California, although the major deposits* occur within the area underlain by the Sierra Nevada batholith. As more or less typical of the many occurrences that have been described, may be cited the Round Valley deposit (Chapman, 1937) and the Pine Creek deposit (Lemmon, 1941). The extensive literature on this subject has been summarized by Kerr (1946). (See also Bateman and Irwin, Contribution 4, Chapter VIII).

The iron deposits of southern California are more abundant and are even more impressive as examples of bulk metasomatism on a large scale. Although some of them had been studied and described more than 40 years ago (Harder, 1912), it was not until World War II that any of the iron deposits were brought into commercial production. Extensive mapping and drilling in several areas have disclosed reserves totalling more than 50 million tons of iron ore, the bulk of which is attributable to contact metamorphism and to hydrothermal activity closely associated therewith. Descriptions of the most significant deposits have been brought together in Bulletin 129 of the California State Division of Mines (1948).

In general the chief minerals of these iron deposits are magnetite and hematite, with some maghemite, and they occur at or close to contacts between granitic (tonalite, quartz monzonite, etc.) intrusives and calcareous country rock. At the Eagle Mountains deposit (Hadley, 1948), much the largest of this group, an early thermal phase of metamorphism produced such minerals as diopside, actinolite, grossularite, wollastonite, scapolite, and labradorite. These are found chiefly in the more impure calcareous beds, and metamorphism of the purer dolomite appears to have resulted mainly in recrystallization. A later, and more distinctly hydrothermal phase of metamorphism led first to formation of tremolite in the dolomite, and then to serpentinization, and to deposition of the iron ores. Although most extensively developed in the calcareous country rock, iron ores are present in silicated zones and even in quartzite (fig. 5).

Minuscule as compared to the iron deposits in terms of tonnage, and yet of sufficient scientific interest to deserve mention here, are the cassiterite-bearing contact-metamorphic deposits in the vicinity of Gorman (Wiese and Page, 1946). Here Paleozoic sediments have been invaded by intrusive rocks of late Mesozoic age, with attendant development of lime-silicate hornfelses, especially in inclusions that lie within the igneous rocks. Cassiterite, regarded as a rather uncommon constituent of contact zones (Lindgren, 1933, p. 727), was obtained commercially from these deposits to the extent of a few tons during World War II. It occurs at or very close to the margins of granitic contacts against the limestone.

Contact action involving magnesium metasomatism is by no means common, and yet some striking illustrations of this are to be found in southern California, particularly in the southern Death Valley-Kingston Range area. Here Wright (1952) has pointed out the remarkably close control of talc formation by (1) the host rock—carbonate strata in the basal portion of the Crystal Spring formation of the late pre-Cambrian Pahrump series—to which all of these deposits are confined, and by (2) the juxtaposition of a thick diabase sill to which the metamorphism and metasomatism are ascribed. Throughout an area of more than 1,000 square miles, talc can be found in nearly all places where a contact between these two rocks is exposed; at several such localities, important commercial concentrations occur (fig. 6). It is interesting to note that there is a direct correlation between the thickness of the diabase intrusive, which ranges from 200 feet to as much as 600 feet, and the size of the silicated zone in which talc and tremolite are the principal

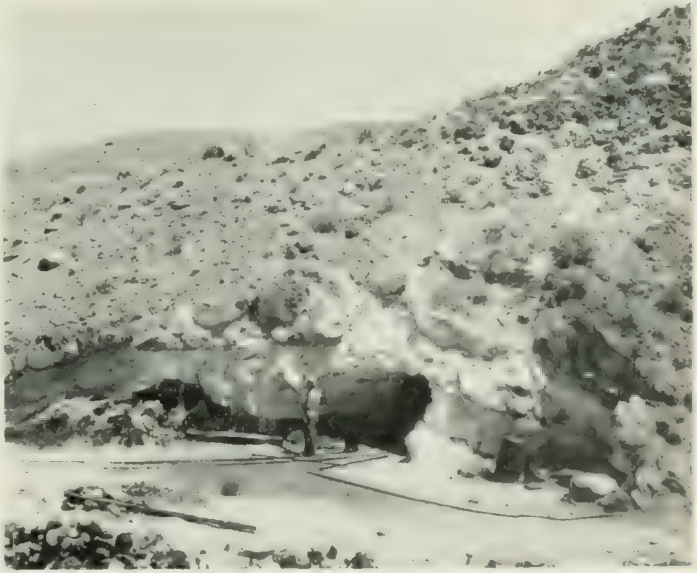

FIGURE 6. Body of talc-tremolite rock at contact between diabase and dolomite, all in the pre-Cambrian Crystal Spring formation. Acme talc mine, San Bernardino County. *Photo courtesy Lauren A. Wright, California Division of Mines.*

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* To avoid possible confusion of types, it perhaps should be pointed out that the important scheelite deposits at Atolia and at Darwin are more properly to be classed as hydrothermal vein types, rather than as contact-metamorphic deposits.

minerals. The history of the alteration starts with a veining of the original carbonate rock by tremolite, alkali feldspar, serpentine, and talc. This is followed by a corrosion and veining of tremolite by serpentine and talc, and next comes a rimming and veining of serpentine grains by talc. Finally, the tremolite is corroded by carbonate, and all of the other minerals are transected by carbonate veinlets. The replacements seem to have taken place on a volume-for-volume basis.

Should the Kramer borate deposits be included among examples of contact metamorphism? If so, they should be referred to as being economically, if not also mineralogically, the most famous of California's contact-metamorphic deposits, and they may thus provide a fitting conclusion to this brief paper. Even the most recent discussions (Connell, 1949) of the origin of the million-odd tons of the unique mineral kernite indicate that there is not yet any generally accepted hypothesis. All who compare the composition of the much commoner and better understood mineral borax ($Na_2B_4O_7 \cdot 10H_2O$) with that of kernite ($Na_2B_4O_7 \cdot 4H_2O$) are struck by the probability that at some stage in the paragenesis, borax has been partially dehydrated to yield kernite (see Mumford, Contribution 2, Chapter VIII).

Schaller (1930), assuming that the basalt known to underlie the deposits might be intrusive, suggested that the thermal action of such an igneous rock upon already accumulated borax would account for the kernite. In this case, we have a relatively simple (albeit unique in terms of its product) example of thermal metamorphism. But the work of Gale (1946), based upon a study of much more extensive underground exposures than were available to Schaller, seems to indicate that the underlying basalt was extrusive, and that the borax beds that overlie it are therefore younger. Nevertheless, Gale suggests that the basalt was still giving off heat at the time when borax-laden lake waters accumulated above it, and that this thermal effect aided in the precipitation of borax and possibly also in its partial dehydration to kernite. That some volcanic phenomena still were active in the vicinity after accumulation of the borax is attested by small amounts of realgar and orpiment found in the deposits.

If, as has been suggested, the basalt did contribute to the thermal metamorphism of the borax, the situation is truly unique. In all other known examples of contact metamorphism, the metamorphosed rock was in place at the time of the igneous invasion. Thus spatially, as well as thermally, the igneous rock plays the dynamic role; the country rock, the passive role. But at Kramer, it might be conjectured that the igneous rock was *in situ* and that subsequently the country rock moved, by means of sedimentary accumulation, into position for its metamorphism. However fantastic such speculation may be adjudged, it is fair to conclude that such an extensive deposit of such a unique mineral as kernite may well deserve a unique explanation!

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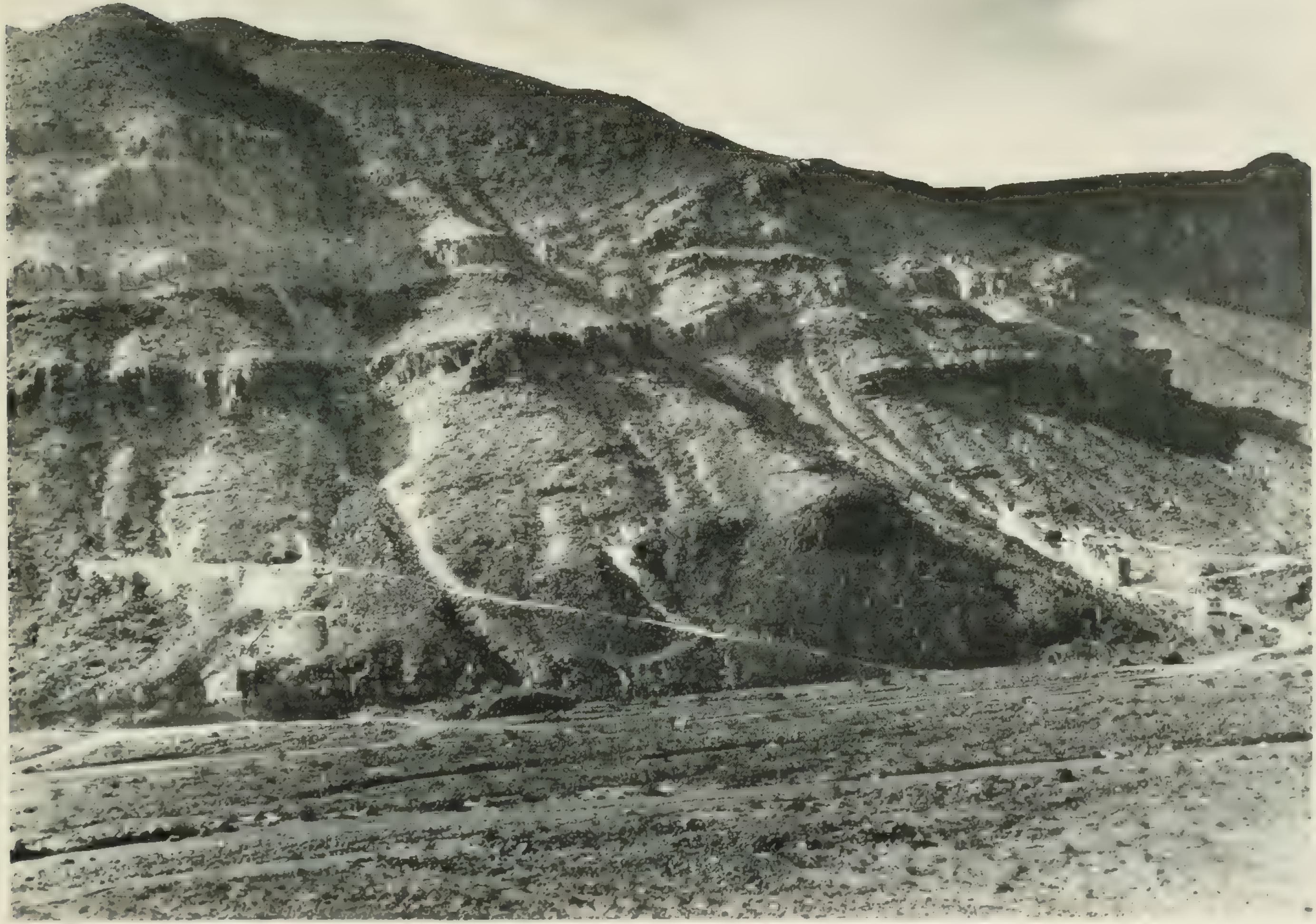

FIGURE 7. View southward of talc-bearing zone in Warm Spring Canyon, southeastern Panamint Range, Inyo County, California. The talc is an alteration of siliceous carbonate strata and has formed along the upper margin of a diabase sill. Another diabase sill forms the skyline, but shows very little contact metamorphism. All of these rocks are part of the Crystal Spring formation of later pre-Cambrian age. *Photo by Lauren A. Wright.*

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7. CONTACT METAMORPHISM AT CRESTMORE, CALIFORNIA[*]

By C. Wayne Burnham [†]

Introduction. The Crestmore limestone mine and quarries of the Riverside Cement Company, located 3 miles north of Riverside, California, have received much attention during the past four decades from mineralogists and petrologists the world over, principally because of the occurrence there of a great variety of contact-metamorphic minerals. Most of the 20 or more published accounts dealing with the Crestmore deposits have been concerned primarily with description of the minerals and discussion of their paragenesis. The present paper is a preliminary and condensed version, mainly descriptive, of the results of a study aimed primarily at defining the occurrence and genesis of the minerals and rocks.

The contact zones lie between magnesian limestones and quartz diorite, and between the same limestones and a relatively small intrusive mass of quartz monzonite porphyry. The limestones occur as lenses of variable thickness and lateral extent within a thick section of predominantly siliceous metamorphic rocks, masses of which occur typically as roof pendants or screens in the intrusive rocks of the southern California batholith. The younger rocks of this composite batholith have been dated tentatively as Upper Cretaceous, and hence the engulfed metamorphic rocks, which in this area have yielded no fossils, are Mesozoic or older.

Pre-batholithic Metamorphic Rocks. The pre-batholithic rocks in the immediate vicinity of the Crestmore quarries consist mostly of coarsely crystalline magnesian limestones and subordinate feldspathic biotite-quartz gneisses, schists, and hornfelses. The limestones form two stratigraphic units, the lower of which is known as the Chino limestone and the upper as the Sky Blue limestone. The Chino limestone locally is as much as 400 feet thick, and recent diamond drilling east of the quarries indicates that the Sky Blue limestone may be 500 feet thick.

Separating these two limestones are gneissic hornfelses and schists that have been largely displaced and, to a small extent, replaced by a sill-like mass of quartz diorite. The noncalcareous metamorphic unit varies strikingly in thickness across the area, and ranges from 70 feet or less east of the Commercial quarry (see pl. 1) to more than 200 feet south of this quarry. These rapid changes do not appear to have resulted from deformation, and are therefore interpreted as the result of rapid facies changes between limestones and siliceous rocks. Additional tabular masses of gneissic hornfels and schist underlie and locally interfinger with the Chino limestone.

The trend of foliation in the metamorphic rocks is slightly west of north, and the dip ranges from 18° to 70° east. The steepest observed dips are in the vicinity of the Crestmore mine. This general attitude conforms to the regional homoclinal structure in the metamorphic rocks that are more extensively exposed south of Riverside, and to the flow structures in the igneous rocks of the batholith in the vicinity of Riverside. In many places, however, the attitude of the foliation varies considerably, owing to mild deformation accompanying intrusion of the quartz diorite. These deformational effects, as well as the general structural relations of all the rock units, are shown in plate 1.

The chemical and petrographic characteristics of both limestone units are similar in every respect. Both units are composed of alternating layers of predazzite and of light gray, coarsely crystalline limestone; this layering reflects original bedding prior to metamorphism. Except for the magnesium content, which, calculated as the carbonate, rarely exceeds 25 percent of the brucite-rich layers, the limestones are relatively pure. A weighted average of about 90 composite analyses of both limestone units, including a few thin chert-bearing zones, indicates over-all silica and alumina contents of 2.0 percent and 0.4 percent, respectively. The brucite grains in the predazzite range in diameter from half a mm. to 2 mm., and commonly have a crude octahedral form. Specimens of predazzite from the Jensen quarry, 3 miles west of Crestmore, contain octahedral crystals of periclase in all stages of alteration to brucite, and clearly indicate a secondary origin for the brucite.

Quartz Diorite. The country rock of the Crestmore region is principally a hornblende-biotite quartz diorite,[‡] the Bonsall tonalite of Larsen (1948), and constitutes the northernmost known exposures of the intrusive rocks of the southern California batholith. It is generally a coarse-grained rock with hypautomorphic texture. The plagioclase is a calcic andesine that contains an average of 44 percent anorthite. The modal analysis in column 1 of table 1 is an average of three determinations on samples taken from three widely separated places in the area, and is thought to be representative of the bulk of the rock. Although this rock generally appears to be of uniform composition, some distinct local variations result in types that range from quartz monzonite to hornblende gabbro.

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[‡] The igneous rock terms used herein are based on the classification by Johannsen, Albert, 1932, A descriptive petrography of the igneous rocks, vol. 1, pp. 141-161, Univ. of Chicago press, Chicago, Illinois.

Table 1. Mineral composition of intrusive rocks of the Crestmore area.

Mineral	1	2
	Quartz diorite	Quartz monzonite prophyry
Plagioclase	56.7% (An44)	30.7% (An32)
Potash feldspar	0.3	34.5
Quartz	21.5	28.0
Pyroxene	1.4	5.2
Hornblende	9.1	0.6
Biotite	10.9	0.1
Accessories	0.1	0.7
Total	100.0%	99.8%

The structural elements of the quartz diorite consist of: (1) abundant ellipsoidal inclusions of gabbroid rock which show preferred orientation of their axial elements; (2) strong gneissic layering commonly developed near contacts with limestone; and (3) a planar structure that rarely is detected in hand specimen or thin section, but which clearly is a cause of a consistent westerly deflection of vertically directed diamond-drill holes. All of these elements strike approximately north and dip moderately eastward.

The contact zone between quartz diorite and limestone is less than a foot thick in most places, and rarely is more than 2 feet thick. The minerals most characteristic of this zone are brownish grossularite garnet, grass-green diopside (diallage), and colorless wollastonite. Minor amounts of quartz, clinozoisite, and scattered grains of sulfides also are present. A nearly vertical pipe of highly siliceous rock that penetrated the Chino limestone in the Crestmore mine was fringed with masses, several feet thick, of pyrrhotite, sphalerite, and other sulfides. This pipe probably was derived from the quartz-diorite magma, as were similar axinite-bearing pipes discovered more recently in the Chino limestone.

Quartz Monzonite Porphyry. Exposed in both the southern and northern parts of the upper face of the Commercial quarry are blocky masses of very light gray quartz monzonite porphyry. The southern and structurally lower mass is the exposed part of an irregular pipe that was intruded upward from the east along the contact between Sky Blue limestone and the underlying quartz diorite (see pl. 1.). The northern and structurally higher mass also was intruded upward from the east as an irregular pipe-like mass, but it lies wholly within the Sky Blue limestone.

The texture of the porphyry is mainly xenomorphic porphyritic, but in detail it is highly variable, especially with respect to grain size and relative abundance of phenocrysts. The phenocrysts, which generally constitute about 10 percent and rarely exceed 25 percent by volume of the rock, are anhedral and range from 1 mm. to 7 mm. in diameter. They are andesine (An37), and are set in a microcrystalline groundmass of sodic andesine (An31), orthoclase, quartz, and variable minor amounts of green pyroxene, sphene, and apatite. Within a few feet of the contact with quartz diorite, the porphyry contains from 2 to 5 percent of dark minerals, mainly hornblende and biotite. Coincident with this change from pyroxene to hornblende and biotite, the sphene of the normal porphyry gives way to ilmenite or titaniferous magnetite with reaction rims of sphene. In column 2 of table 1 is presented an average of 11 modal analyses of quartz monzonite porphyry.

In the central parts of the larger masses, the porphyry is very leucocratic and contains 3 percent or less of dark minerals. Within a few feet or a few tens of feet of limestone-derived contact rock, the amount of diopsidic pyroxene increases to as much as 45 percent of the rock, strongly suggesting that the porphyry magma was contaminated by limestone. However, the anorthite content of the plagioclase in the groundmass evidently was little affected until the degree of contamination became very great. The contrast between the dark minerals of the porphyry near the quartz diorite, on one hand, and near limestone, on the other, emphasizes the effects of slight changes in composition on the stability relations among certain minerals.

The quartz monzonite porphyry is marked by joints, flow layering, and a weak lineation. Near station A (pl. 2 and fig. 2), in the southern part of the Commercial quarry, two sets of joints are conspicuous. One set, which parallels the plane of foliation and flow layering, strikes N 48° W and dips 28° NE near the footwall contact, but strikes N 30° W and dips 30° NE near the hanging wall. The other set strikes nearly east and dips 86° to 87° N. Near the footwall the line of intersection of these two sets of joints defines a lineation that nearly coincides with another lineation formed by the preferred orientation of mineral grains. Furthermore, this direction is roughly the same as the direction of flow of the magma, as determined by the shape and suspected source area of the porphyry intrusive.

Pegmatite dikes cut the contact rock, contaminated rock, and marginal parts of the porphyry. They clearly are related in origin to the porphyry, for all gradations between the two rock types have been found in a single dike or lens. Where they occur in the marginal parts of the porphyry, these dikes and lenses have two preferred attitudes, one parallel to the gently northeast-dipping joints mentioned above, and the other striking N 15° W and dipping 50°-80° E. This latter attitude is the more common, and is roughly parallel to that of another poorly developed set of joints. It is likely that both sets of joints exercised some control during emplacement of the pegmatite bodies.

Contaminated Rocks. The group of contaminated rocks is genetically related to the quartz monzonite porphyry, but these rocks differ from the porphyry because of assimilation of limestone. The group may be subdivided into two types that generally can be distinguished by differences in color, texture, composition, and occurrence, although nearly all transitions between the two have been observed. The less extensive type is very dark colored and porphyritic, and generally occurs as small, pipe-like masses or stringers. These stringers apparently represent the terminal parts of apophyses from the main mass of porphyry that penetrated contact rock and possibly limestone. Compositionally, this type ranges from a syenodiorite to a gabbro, the median probably lying in the diorite group. An extremely basic member is represented by the modal analysis in column 1 of table 2.

The more common type of contaminated rock generally is lighter in color, less porphyritic, and coarser grained. It occurs as relatively large masses that have engulfed large blocks of garnet-rich contact rock. These masses are marginal to the bodies of quartz monzonite porphyry and doubtless grade into them. In column 2 of table 2 is presented a modal analysis of an extremely potassic member of this type, which occurs as small stringers in contact rock near station J (pl. 2). Column 3 represents an average of 15 modal analyses of both types of contaminated rock. It is clear that the average contaminated rock, if such an average is significant, can be classified as a pyroxene monzonite.

Table 2. Mineral composition of contaminated rocks.

Mineral	1	2	3
Plagioclase	50.1% (An70)	------	42.4% (An40)
Potash feldspar	------	83.4%	30.3
Quartz	------	------	0.4
Pyroxene	47.7	9.8	24.5
Sphene	2.2	0.3	1.8
Wollastonite	------	6.5	0.5
Total	100.0%	100.0%	99.9%

In addition to the minerals listed in table 2, minor amounts of biotite, hornblende, grossularite garnet, apatite, and rare scapolite and ilmenite or titaniferous magnetite are present in the contaminated rocks. Alteration products, which are not abundant, include calcite, zoisite, chlorite, and kaolinite.

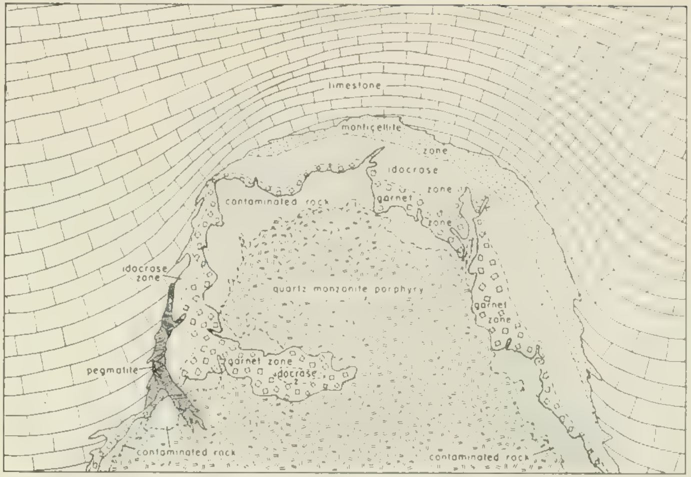

Figure 1. Idealized north-south cross section (not to scale) through the quartz monzonite prophyry intrusion at Crestmore.

Perhaps the most important mineralogical feature of the contaminated rocks is the occurrence, very near the contacts with garnet-rich contact rock, of two types of potash-bearing feldspar; these consist of an early, relatively coarse-grained feldspar with optical properties similar to those of anorthoclase, and a later, interstitial, fine-grained feldspar resembling common orthoclase. Much of the coarser-grained feldspar very near the contact is perthitic, a feature that is absent from the alkali feldspar of the quartz monzonite porphyry. Myrmekitic intergrowths of quartz and plagioclase have the same distribution as perthite, in that they are common in the contaminated rocks and nearly absent in the porphyry.

Many relatively small masses of dark, fine-grained, schistose rocks occur in the northern part of the Commercial quarry, especially in contaminated rock. Some of these masses are only partly schistose, the remainder appearing as massive porphyritic contaminated rock. Under the microscope, however, even the apparently massive part commonly is transected by numerous shear planes, along which there has been some displacement and granulation. In addition to these mechanical effects, some of the masses have been extensively recrystallized, with formation of biotite and hornblende as the principal dark minerals. These rocks apparently represent early stringers of porphyritic contaminated rock that were deformed by the subsequent intrusion of the main mass of porphyry. The space relations of the contaminated rocks to the quartz monzonite porphyry and to contact rock, as well as the relations of the various zones of contact rock to the parental limestones and intrusive rocks, are shown schematically in figure 1.

Quartz Monzonite Pegmatites. Pegmatites thought to be genetically related to the quartz monzonite porphyry are of common occurrence at Crestmore, although their total volume is relatively small. Near their source the dikes apparently differ very little in mineralogy from the porphyry, although the relative proportions of the constituent minerals might be different. The plagioclase is a calcic oligoclase or sodic andesine, and the potash feldspar is commonly perthitic. Microcline twinning is uncommon in those pegmatites that lie within or near the porphyry. On the other hand, the dikes in contact rock and near limestone show increasing amounts of twinned microcline, and locally contain abundant brown andradite garnet.

In the lower part of the Commercial quarry, along the face below station N, is a thin, discontinuous sheet or mesh of microcline crystals and, locally very near the limestone, wollastonite blades. This rock apparently represents the silicate end-product of crystallization of the pegmatite magma. The contact zone between the limestone and this wollastonite-microcline pegmatite generally is not more than half an inch thick, and locally the rocks are in knife-sharp contact. Where present, the transition zone ordinarily consists of wollastonite and minor amounts of diopsidic pyroxene.

Scattered patches and vein-like masses of epidote-microcline-calcite-quartz rock, somewhat pegmatitic in appearance, extend from station E, on the upper face of the Commercial quarry, downward along the face to the north. Near station E they consist principally of massive quartz, microcline, and epidote, but toward the north the ratio of calcite to quartz increases to such an extent that near station F they are mainly coarsely crystalline aggregates of greenish-gray calcite enclosing large, euhedral crystals of epidote. Aside from their coarse and variable grain size, these rocks bear little resemblance to the normal pegmatites, and they may well have been more hydrothermal in origin than the normal pegmatites.

Contact Rocks. Surrounding the quartz monzonite porphyry and related contaminated rocks where they have invaded the Sky Blue limestone is an aureole of contact rock, the product of silica and alumina metasomatism. This aureole ranges in thickness from less than an inch to 50 feet. In addition, many remnants of limestone that were engulfed by the porphyry have been transformed into contact rock that consists of diopside, wollastonite, and grossularite garnet, with minor calcite and quartz. The quartz is present very near the intrusive contacts. Garnet is by far the dominant mineral in this type of contact rock, which is so abundant that garnet is therefore the dominant contact silicate mineral at Crestmore. Diopside and wollastonite generally are present in about equal proportions; locally, however, their relative proportions are highly variable, and apparently reflect the distribution of magnesium in the original limestones.

The diopside-wollastonite-garnet assemblage is also characteristic of the innermost zone of the contact aureole, and as such constitutes most of the dark outcrops near the summit of Sky Blue Hill, as well as the dark brown exposures above stations B and C on the upper face of the Commercial quarry (pls. 1, 2). Near the porphyry contact, in the vicinity of station B, this rock locally contains numerous calcite-filled veinlets, along the walls of which scapolite crystals commonly occur.

On the upper face of the Commercial quarry, above station C, are numerous small stringers of contaminated rock in diopside-wollastonite-garnet rock, and on the slope of Sky Blue Hill, above station D, a mixture of these two rocks in places resembles a "puddingstone," with nodules of diopside-wollastonite-garnet rock in a matrix of dark contaminated rock. The nodules commonly are ellipsoids as much as 10 inches long, and are oriented with their longest axes plunging moderately eastward. In the vicinity of stations F and G, the diopside-wollastonite-garnet rock is noticeably brecciated, and the fragments are set in a matrix of light-colored contaminated rock or, locally, pegmatitic quartz monzonite.

The thickness of the part of the aureole that consists of diopside-wollastonite-garnet rock, and which henceforth will be termed the garnet zone, is highly variable, and ranges from only a few inches near station Q to 25 feet or more above station C. However, in the latter area the garnet zones of the two porphyry pipes overlap, producing an unusually thick mass of garnet rock.

The diopside-wollastonite-garnet assemblage also forms sheaths that surround the small stringers of contaminated rock that cut idocrase and monticellite-rich contact rocks between stations I and M. The sheaths range in thickness from 2 to 10 inches, and are very fine grained. The small blades of wollastonite appear to radiate outward from the stringers.

A zone characterized by the mineral idocrase lies beyond the garnet zone away from the porphyry, and occupies an intermediate position in the contact aureole. Associated with the idocrase is a great variety of minerals, but because of the intermediate position of this zone, the associated minerals in the inner part generally are different from those in the outer part. This variability in mineral assemblages is in contrast to the simple and monotonous garnet-zone assemblage. In the inner part of the zone, any one or all of the minerals of the garnet zone may be associated with idocrase, whereas monticellite is a common constituent in the outer part of the zone. However, the diopside of the garnet zone generally is darker green than that in the idocrase rock.

In addition to monticellite, several minerals make their first appearance in the idocrase zone. Two of these are wilkeite and its alteration product, crestmoreite, which are widespread minor constituents of both this zone and the monticellite zone. They also range somewhat beyond into the blue calcite of the Sky Blue limestone. Pink wilkeite occurs in the ridge between the Commercial and Wet Weather quarries, but has not been found recently *in situ* in the Commercial quarry. As far as can be determined, pink wilkeite was restricted to idocrase-zone rocks, whereas a yellow variety, which occurs as numerous wheat-shaped grains, is much more widespread.

Micaceous minerals are common in the outer part of the idocrase zone and in the inner part of the monticellite zone. Sheets of green phlogopite as much as 4 centimeters across occur in monticellite-idocrase rock above station K, and colorless xanthophyllite is abundant in the pale green idocrase rock near station C. The emerald green micaceous mineral that formerly was abundant in the diopside-bearing idocrase rock in the vicinity of station Q, although resembling xanthophyllite, yields an x-ray diffraction pattern that resembles neither phlogopite nor xanthophyllite. At the present time this mineral remains unidentified.

The monticellite zone lies beyond the idocrase zone and extends to the limits of silica and alumina metasomatism. Its contact with the idocrase zone generally is gradational, and is arbitrarily drawn where monticellite or its typically associated minerals constitute as much as 50 percent of the rock. In addition to monticellite, the minerals characteristic of this zone include gehlenite, spurrite, merwinite, tilleyite, forsterite, scawtite, spinel, and plazolite (?).

The most accessible exposures of the monticellite zone are in the lower part of the Commercial quarry, between stations H and M and between stations O and Q. Westward for several feet from station H, which is virtually on the boundary of the contact aureole, the rocks are largely carbonate, but contain abundant small crystals of monticellite and silky white pseudomorphs of crestmoreite after wilkeite. Small crystals of idocrase and spinel also are common minor constituents. Wilkeite, in relatively large lemon-yellow crystals, locally is common in the monticellite and monticellite-idocrase transition zones, where it occurs in and around residual masses of blue calcite. Dark green spinel, another common constituent, appears to be restricted to the monticellite zone. Above station I the massive gray rock generally contains sub-equal quantities of monticellite, gehlenite, spurrite, and merwinite, with minor amounts of idocrase, spinel, and calcite. A short distance northwest of here are a few small masses that resemble coarse-grained aggregates of quartz. Merwinite forms about 90 percent of these masses, the remainder being idocrase, spurrite, and calcite.

Some of the rock near station J contains abundant tilleyite; indeed, from this point southwestward for a distance of 25 or 30 feet, tilleyite, spurrite, and merwinite, together, appear to predominate over monticellite. Monticellite, however, is the most abundant constituent of this zone along the remainder of the face to station M, except above station L, where a relatively small mass of very light gray forsterite-rich rock, streaked with dark, fine-grained spinel, is present. This is the only known occurrence of forsterite at Crestmore; nearly 90 percent of the rock is forsterite at this one place.

Exposures of monticellite-zone rocks along the face between stations O and Q in the lower part of the Commercial quarry are smaller and fewer in number than along the face just described, mainly because the over-all thickness of the metamorphic aureole is not as great. The consequent telescoping of the zones caused a considerable overlap of mineral assemblages. Above station P, for example, wollastonite and idocrase form vermicular growths in host crystals of monticellite in calcite. A mineral that has been tentatively identified as scawtite occurs sparingly about 15 feet south of station P, where it is associated with spurrite, merwinite, gehlenite, idocrase, and calcite. The mass of monticellite-zone rock near station C, in the upper face of the Commercial quarry, consists mainly of merwinite and gehlenite, with subordinate monticellite, spurrite, and plazolite (?).

Limestones and Predazzites. Many small masses of sky-blue calcite are scattered throughout the contact aureole. Most of them appear to be remnants of Sky Blue limestone that persisted unchanged, except for partial recrystallization and blue coloration, during formation of the enclosing silicate rocks. A similar coarsely crystalline blue calcite forms a sort of halo, ranging from less than an inch up to a few tens of feet thick, that surrounds the contact aureole in the Sky Blue limestone. In addition, distinctly bluish calcite has been found as haloes a few inches thick surrounding recrystallized chert nodules in the Chino limestone. These nodules, which occur nearly 100 feet from the quartz-diorite contact, are separated from the enclosing blue calcite by an inch or more of white, sugary to fibrous wollastonite.

The cause of the blue color in this calcite is unknown. Its spatial distribution in relation to the structural features of the area suggests that it is not due to deformationally induced strain. Similarly, it is doubtful that it is due to contained organic matter. On the

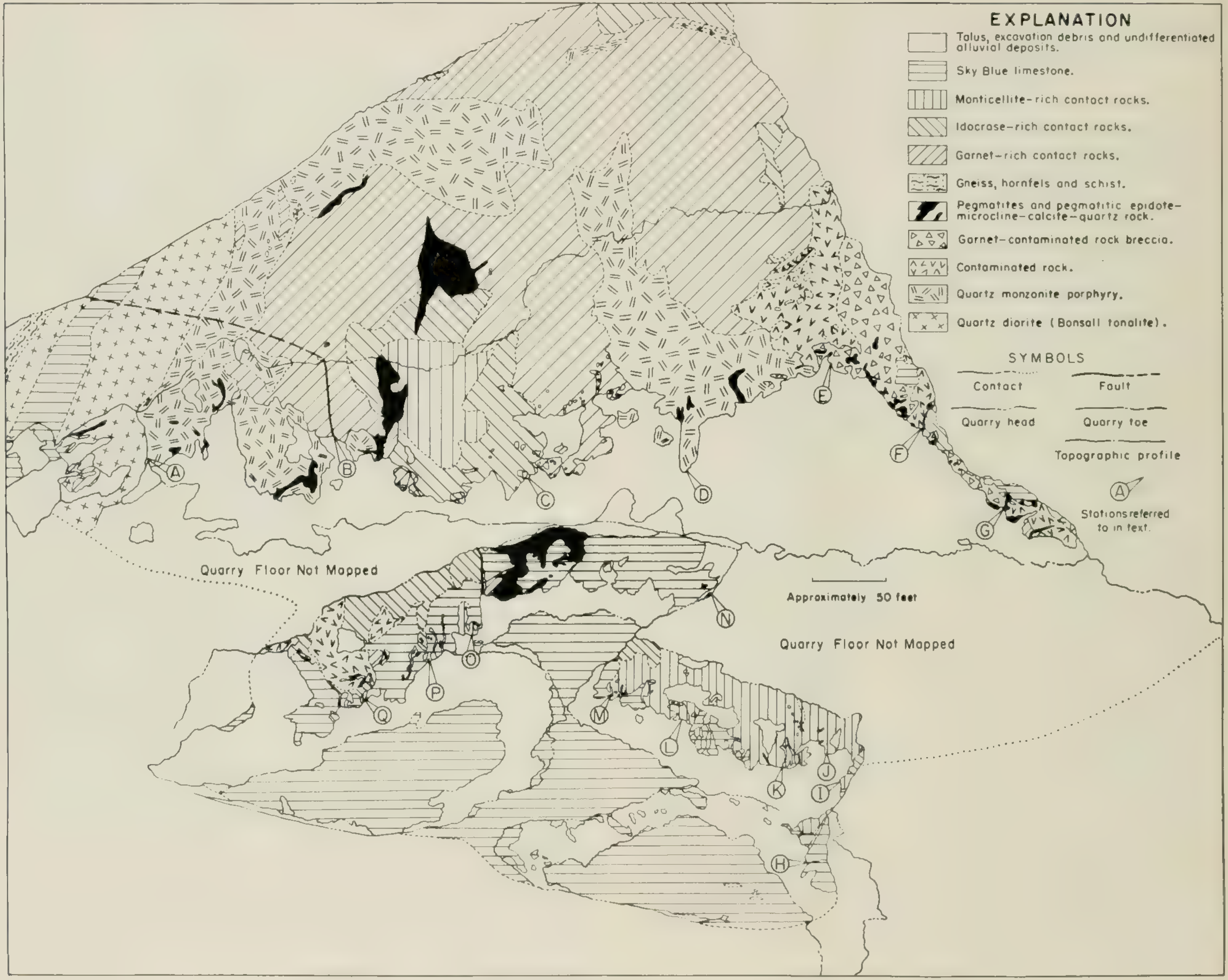
EXPLANATION
Talus, excavation debris and undifferentiated alluvial deposits.
Sky Blue limestone.
Monticellite-rich contact rocks.
Idocrase-rich contact rocks.
Garnet-rich contact rocks.
Gneiss, hornfels and schist.
Pegmatites and pegmatitic epidote-microcline-calcite-quartz rock.
Garnet-contaminated rock breccia.
Contaminated rock.
Quartz monzonite porphyry.
Quartz diorite (Bonsall tonalite).
SYMBOLS
Contact
Fault
Quarry head
Quarry toe
Topographic profile
A
Stations referred to in text.
Quarry Floor Not Mapped
Approximately 50 feet
Quarry Floor Not Mapped
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q

FIGURE 2. Generalized geologic map of faces of the Commercial quarry, Crestmore. Compare with figure 3

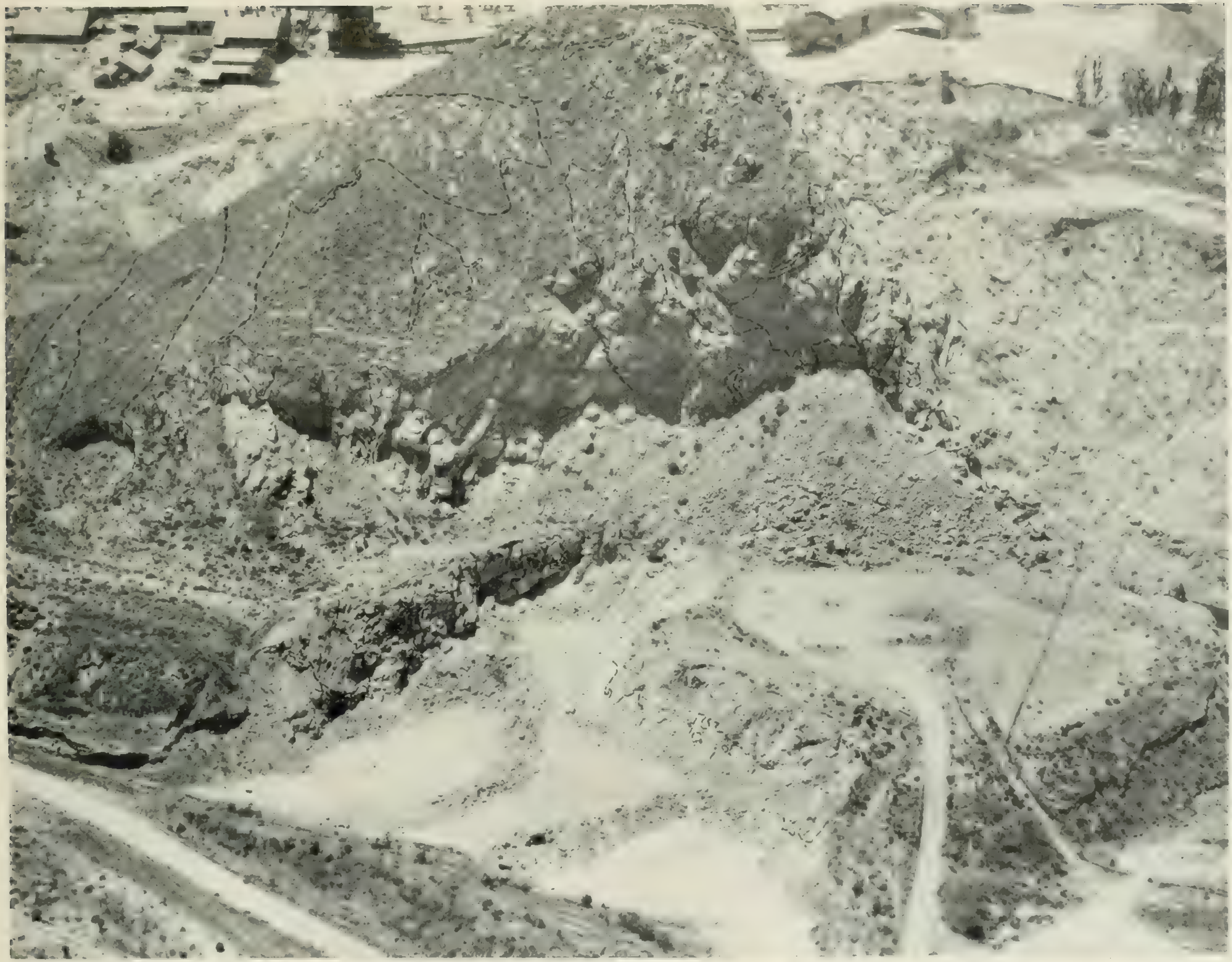

FIGURE 3. Oblique aerial view of the Commercial quarry, Crestmore. *R. C. Frampton photo.*

other hand, its distribution in the calcite does suggest that it might be related to lattice defects or to the introduction of minor or trace impurities during metamorphism. Although the most intense blue color is associated with brucite-free calcite, bluish predazzite also has been found.

Outside the contract aureole and beyond the halo of blue calcite, the magnesian limestones that were transformed into coarsely crystalline gray limestones and predazzites, either prior to or at the time of intrusion of the quartz diorite, were little affected by the quartz monzonite prophyry except in a few places near the contact, where scattered crystals of yellow chondrodite are present. This extremely abrupt change from rocks of very high metamorphic rank to unaffected limestones evidently is due to high thermal stability of the brucite-calcite assemblage and, perhaps more important, to the extreme instability of this same assemblage in the presence of very hot silica-bearing solutions.

Origin and Emplacement of the Quartz Monzonite Porphyry. Present evidence indicates that the quartz monzonite prophyry was intruded as a pipe-like body, 200 to 300 feet in diameter, upward and northward from points beneath the southeast corner of the area (see pl. 1). The wall rocks of the pipe in this part of the area were quartz diorite and a small remnant of the Chino limestone. At the point where the pipe intersected a large fragment of metamorphic rocks that directly underlie and interfinger with the lower members of the Sky Blue limestone, it split into two smaller pipes, one of which extended westward along the contact between quartz diorite and the metamorphic rocks.

The remainder of the porphyry magma continued on its northerly course, passing through the remnant of metamorphic rocks and through additional quartz diorite to the quartz diorite-Sky Blue limestone contact. Within the Sky Blue limestone, the porphyry formed a complex network of anastomosing pipes and stringers, the main mass of which was directed either westward along and near the footwall contact, or steeply upward into the limestone. As far as can be determined, the porphyry does not extend for more than a short distance north of the present south wall of the Wet Weather quarry.

The mechanical effects of the emplacement of the porphyry were highly variable. The quartz diorite apparently was little affected, but the Sky Blue limestone was arched up sharply into an eastward-plunging anticline. The distribution of CaO in contaminated and uncontaminated porphyry indicates that less than 15 percent of the space now occupied by the intrusive rock can be accounted for by the assimilation of limestone; hence, it might be assumed that the porphyry made room for itself largely by doming the limestone roof rocks.

The differences in the metasomatic effects associated with the quartz monzonite porphyry, as compared with those of the quartz diorite, must be related in some way to differences in physico-chemical conditions at the time of emplacement, for the same limestones were the host rocks in both cases. Although absolute values for the variables of temperature, pressure, and composition would be difficult to establish, comparative values can be deduced with a certain degree of probability on the basis of composition and internal fabric of the crystallized products.

The quartz diorite exhibits features of texture and internal structure that are compatible with a magma of high viscosity and incompatible with one of low viscosity, and hence it is inferred that the magma contained a relatively high proportion of crystallized material at the time of its emplacement. This in turn implies that: (1) temperatures in the magma were in the lower part of the range of crystallization, and (2) the amount of water and other volatile constituents in the magma was relatively small.

The implication that the magma was deficient in water at the time of its emplacement follows from a consideration of the role played by this compound. Presumably it tends to reduce the viscosity of a magma by preventing the formation of large polymers of silica, and conversely, a deficiency in water and certain other volatiles permits the formation of these large polymers of silica, with attendant increases in viscosity of the liquid phase. Therefore, it is inferred that at the time of its emplacement, the viscous quartz diorite magma probably was deficient in water. Furthermore, because of the lack of the abundant water and uncombined silica that are necessary for large-scale silica metasomatism, the quartz diorite magma produced only a foot or two of silicate contact rock where it encountered limestone. The water-deficient condition that is here postulated to account for the thin contact zone between quartz diorite and limestone might have resulted from early crystallization of the hydrous minerals hornblende and biotite, which make up about 20 percent of the quartz diorite.

In contrast, textural evidence indicates that the quartz monzonite porphyry was not much more than 10 or 15 percent crystalline at the time of initial intrusion, and that therefore its temperatures probably were in the higher part of the crystallization range. Furthermore, because the porphyry magma apparently was originally very poor in iron and magnesium, necessary components of hornblende and biotite, none of the original water of the magma was fixed in early solid phases. Thus with high temperatures and with the existence of abundant water and uncombined silica and alumina, some of the most important conditions for large-scale metasomatism were satisfied. However, unless conditions in the system had been favorable for the separation of these potential metasomatizing solutions, the surrounding limestones obviously would have been little affected.

The derivation of the metasomatizing solutions from the residuum of crystallization is precluded, for there is strong evidence that extensive metasomatism actually preceded final emplacement and crystallization of the porphyry. Therefore, it is suggesed that the sudden relief of confining pressure on the highly fluid porphyry magma upon its entry into the easily deformable limestones, coupled with a copious evolution of CO_2 by reaction beween magma and limestone, caused the separation of large quantities of CO_2-rich aqueous solutions that served as transporting media for heat, silica, and alumina.

Origin of the Contact Rocks and Metamorphic Zones. An adequate theory for the origin of the contact rocks at Crestmore must explain the following features: (1) the occurrence of relatively rare, presumably high-temperature contact minerals such as merwinite and spurrite; (2) the very sharp contact between unaffected limestones and rocks composed of these minerals; and (3) the general zonal distribution of mineral assemblages with the monticellite-zone assemblage, containing many of the critical minerals of the sanidinite facies, adjacent to the unaffected limestones; with the garnet-zone assemblage, the characteristic minerals of which are critical for the pyroxene hornfels facies, lying next to the intrusive; and with idocrase in between.

The occurrence of minerals that presumably require higher temperatures for their formation than ordinarily are attributed to even the hottest granitic magmas is most easily explained as the result of development under non-equilibrium conditions. The large number of mineral phases that can be observed in a single thin section, some of them in reaction relationship, and the consistent decrease in silica content of the contact rocks outward from the intrusive masses, strongly suggest that equilibrium was not generally attained and that the system was essentially open. Under these conditions, the CO_2 evolved during formation of the silicate minerals would have escaped and thereby allowed the reactions to proceed at much lower temperatures than would have been possible in a closed system.

A possible cause of the sharp contact between the monticellite zone and the unaffected limestones may be deduced from the conditions imposed by the nature and position of the zones themselves. Specifically, the temperature of metamorphism was sufficient, even in the outermost part of the contact aureole, for the formation of the monticellite-zone assemblage, and, in order to account for the absence of a so-called lower-grade zone (characterized by such minerals as tremolite) beyond the monticellite zone, these temperatures must have been reached prior to, or at the time of, introduction of the silica and alumina. The high thermal conditions thus imposed upon the calcite-brucite assemblage rendered it highly reactive to the silica- and alumina-bearing solutions, and therefore capable of rapidly and almost quantitatively removing these constituents from the solutions.

Inasmuch as the relative positions of the contact zones are just the reverse of what would be expected on the basis of thermal zoning, it is concluded that, during metamorphism, either the temperature gradient was very small from the intrusive outward to the boundary of the aureole, or metasomatic effects completely overshadowed the thermal effects. If metasomatic processes actually were responsible for the zoning, the mineral assemblages of each zone should exhibit some consistent compositional difference with respect to the assemblages of an adjacent zone. That this is the case can be shown by computing the atomic ratios of calcium plus magnesium to silicon for the various minerals of the contact aureole. It is found that the minerals characteristic of the inner or garnet zone have ratios of about 1:1, those characteristic of the outer or monticellite zone, 2:1, and idocrase of the intermediate zone, 1.5:1.

Conclusion. This summary of contact metamorphism at Crestmore would not be complete without at least a brief discussion of the concept advanced by Bowen (1940), wherein it is postulated that various contact minerals are formed in a stepwise sequence by progressive decarbonation of a siliceous limestone or dolomite, as a consequence of rising temperature. The only evidence found at Crestmore to date that supports such a scheme comes from textural studies of the monticellite-zone rocks, which indicate that monticellite, gehlenite, spurrite, and merwinite formed in that order, coincident with Bowen's "index minerals" 6 to 9, inclusive. From the same studies, however, it is evident that the reactions by which these minerals were formed were not, in general, those suggested by Bowen. The principal cause of failure in the attempted application of this scheme appears to stem from the lack of silica in the limestone. The effect of this deficiency of the system was to make the various minerals dependent for their formation on the silica introduced during metasomatism. It is concluded, therefore, that the contact metamorphism at Crestmore should be viewed as progressive decarbonation, at elevated temperatures, attendant upon increasing concentrations of metasomatic constituents, rather than as progressive decarbonation attendant simply upon rising temperatures.

Acknowledgments. The writer is grateful for the wholehearted cooperation of the officials of the Riverside Cement Company, and particularly for their generosity in allowing him complete access to diamond-drill records and cores. Dr. A. O. Woodford and Dr. R. H. Jahns offered many valuable suggestions and criticisms during the course of the work and in the preparation of the manuscript. The Claremont Graduate School supplied funds for the aerial photograph shown in figure 3.

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8. ANORTHOSITE COMPLEX OF THE WESTERN SAN GABRIEL MOUNTAINS, SOUTHERN CALIFORNIA

BY DONALD V. HIGGS *

INTRODUCTION

Anorthosite and related igneous rocks are part of the crystalline complex of the San Gabriel Mountains, in Los Angeles County, California. The area studied (fig. 1) comprises about 60 square miles of the western part of the range, and includes the western two-thirds of the norite-anorthosite complex. The crystalline rocks can be divided into four groups, which are, from oldest to youngest, 1) metamorphic rocks, 2) norite-anorthosite complex, 3) quartz diorite and granite intrusives, and 4) lamprophyre dikes. These rocks form the major part of the structurally high pre-Cretaceous core of the west-trending range. The region is traversed by several high-angle faults, some of which separate the crystalline rocks from Tertiary sedimentary rocks that in general underlie the topographically lower areas.

Foliation in the metamorphic rocks is well defined, and in general attitude it conforms with the regional trend of the San Gabriel Mountains. The norite-anorthosite complex exhibits distinct irregular layering, the spatial relations of which suggest a dome-like structure for the intrusive within the area mapped. The complex is uniformly shattered. The younger quartz diorite and granite intrusives are massive.

METAMORPHIC ROCKS

Amphibolite, hornblende gneiss, biotite-hornblende gneiss, and quartzo-feldspathic gneiss are exposed in a belt north of the Dillon fault, and are the oldest rocks in the area. They constitute a part of the San Gabriel formation of Miller (1934). Foliation is well defined except in the amphibolite, and in most places it dips steeply to the west or southwest. The rocks are in fault contact with norite on the north and with quartz diorite on the south.

Amphibolite makes up about one-tenth of the belt of metamorphic rocks, and is found in the western part. It is a medium-grained, dark greenish gray, granoblastic rock that consists of about 45 percent of xenoblastic to poikiloblastic plagioclase (An50-52), 25 percent of brown xenoblastic hornblende, 20 percent of xenoblastic to sub-idioblastic augite, 5 percent of biotite, small amounts of quartz, and scattered small grains of zircon and apatite. Green hornblende, penninite, biotite, calcite, muscovite, and epidote are secondary minerals derived from the hornblende, augite, and plagioclase.

Gneiss, which forms the larger part of the metamorphic rocks, generally is light gray to bluish gray in the hand specimen. Dominance of hornblende, biotite and hornblende, or quartz and feldspar in a given variety defines it as hornblende gneiss, biotite-hornblende gneiss, or quartzo-feldspathic gneiss, respectively. There is random gradational alternation of layers of the four main rock types, and the layers range in thickness from less than 1 inch to 20 or 30 feet. The gradation in rock type is controlled only by variation in the relative proportions of the minerals.

The dominant minerals in the gneisses are medium- to coarse-grained, sub-idioblastic to xenoblastic plagioclase; medium- to coarse-grained, xenoblastic perthite; fine- to coarse-grained, xenoblastic quartz; fine- to medium-grained, sub-idioblastic to idioblastic hornblende; and medium-grained, sub-idioblastic biotite. In addition, small to large porphyroblastic crystals of garnet are present in some of the more biotite-rich varieties of the gneiss. Secondary minerals include penninite, muscovite, calcite, and epidote.

NORITE-ANORTHOSITE COMPLEX

The norite-anorthosite complex is a dome-like intrusive mass within the metamorphic rocks, and is separable into three major rock types. These are norite, transition rock, and anorthosite, and with them are associated apatite-ilmenite rocks. The three types can be defined, on the basis of percentage of mafic minerals, as: anorthosite . . . 0 to 10 percent, transition rock . . . 10 to 35 percent, and norite . . . 35 to 65 percent. There is complete transition from one rock type to another, with no sharp boundaries between members of the sequence.† The dome-like structure of the complex is indicated by the areal distribution of norite, transition rock, and anorthosite (fig. 1), and by the layering in the norite and transition rock, which dips away from the anorthosite. The norite forms a marginal phase, and grades through the transition rock into the core of anorthosite.

The mineral assemblage of the complex is divided into three groups, magmatic, deuteric, and hydrothermal, on the basis of their sequence of formation (fig. 2). The magmatic minerals crystallized from a melt, the deuteric minerals, in general, formed at the expense of the magmatic minerals, and the hydrothermal minerals formed at the expense of the magmatic and deuteric minerals.

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* Geologist, Shell Development Company, Houston, Texas.

† Excellent exposures of the different rock types are present east of the area shown in figure 1, along the Angeles Forest Highway about 12 miles south of Vincent Siding.

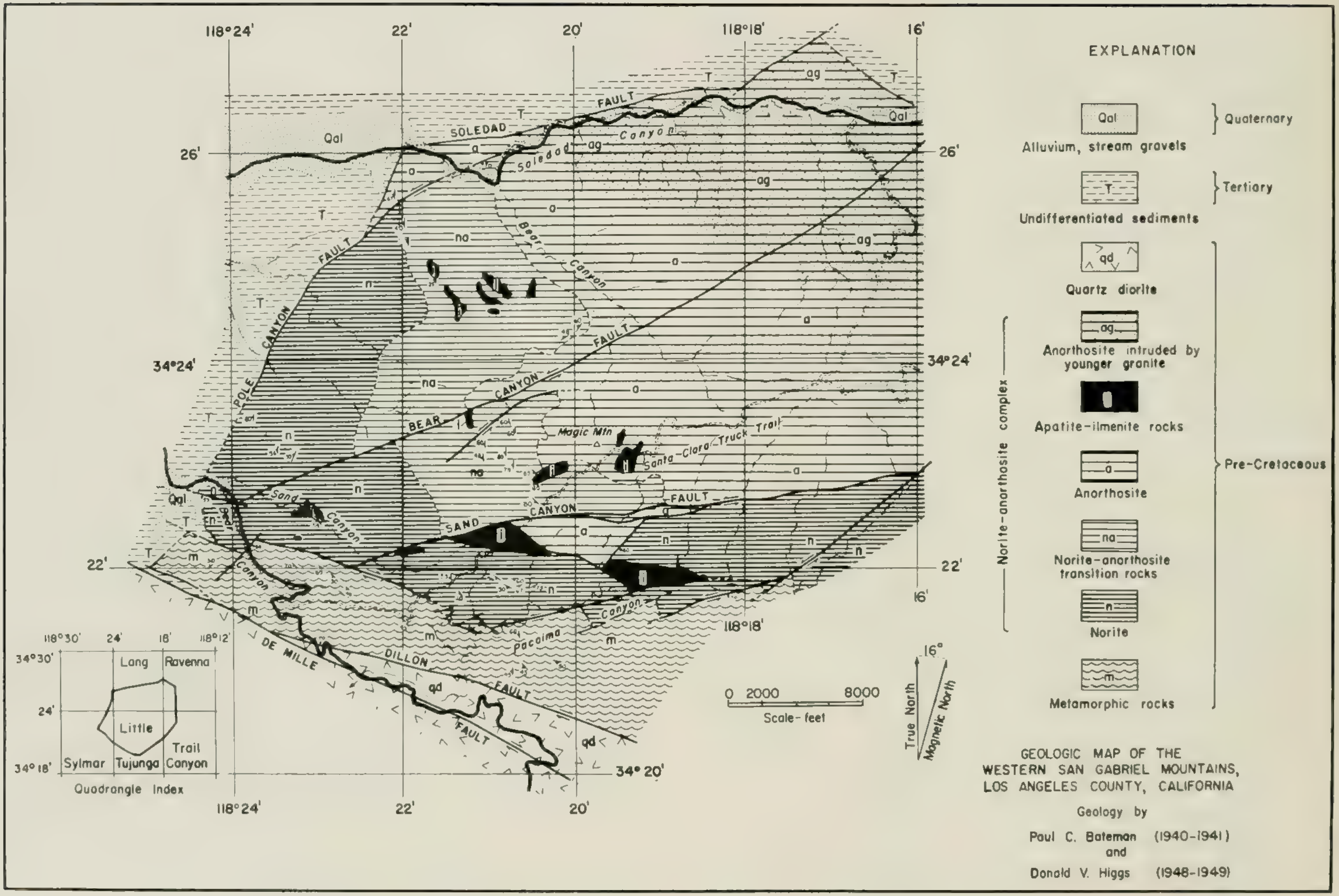

FIGURE 1. Geologic map of the western San Gabriel Mountains, Los Angeles County, California.

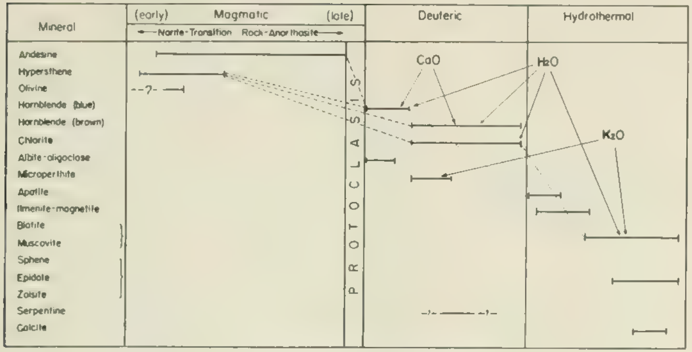

FIGURE 2. Sequence of crystallization of minerals in the norite-anorthosite complex.

The magmatic minerals are plagioclase, hypersthene, and olivine. The plagioclase is remarkably uniform in composition, ranging from An39 to An46, and is unzoned. The andesine is euhedral to subhedral, and is bluish gray to white in the hand specimen. The euhedral crystals are characteristically tabular, commonly elongated parallel to the *a*-axis. They range in size from less than half an inch to as much as 6 feet. Hypersthene occurs as medium- to extremely coarse-grained, euhedral to subhedral crystals that are greenish gray to black in the hand specimen. These crystals range in size from less than 1 inch to 4 feet, and some are inferred to be as much as 10 feet in diameter. The hypersthene is extensively altered. Olivine is present in some of the most mafic parts of the norite as medium-grained, subhedral to euhedral crystals.

The deuteric minerals are plagioclase (albite to oligoclase), microperthite, micro-antiperthite, hornblende, chlorite, and serpentine. The grains of albite-oligoclase were formed along cleavage planes and fractures in crystals of andesine, and as rims on these crystals, especially where the andesine is in contact with hypersthene. Microperthite and micro-antiperthite were developed by replacement of andesine, albite, and oligoclase. Bluish-green hornblende was formed as reaction rims on the hypersthene crystals, and fibrous brown hornblende was developed in the cores of hypersthene crystals. Penninite is found in association with the fibrous brown hornblende. Serpentine was developed by alteration of the olivine.

The hydrothermal minerals are apatite, iron-ore minerals,* biotite, sericite, epidote, calcite, zoisite, and sphene. The apatite is associated with the iron-ore minerals, which replace the mafic minerals of the complex. Biotite is found as a late hydrothermal mineral replacing hypersthene and hornblende. Sericite, calcite, and zoisite are alteration products of andesine and epidote formed after both andesine and hornblende. Sphene is an alteration product of the iron-ore minerals, and is present only in small amounts.

Norite. The marginal facies of the complex is a xenomorphic to hypautomorphic, medium- to coarse-grained rock composed of andesine and hypersthene. Fresh surfaces are dark gray, and upon weathering they become dark brown or black. The coarse-grained norite presents a mottled appearance that is due to light-colored andesine grains embedded in a dark matrix of altered hypersthene. Irregular layering is conspicuous, and becomes progressively more distinct through the gradation into transition rock. Grain size increases inward from the outer margin of the norite, and with this increase the texture changes from dominantly xenomorphic to dominantly hypautomorphic.

Transition Rock. Anorthosite is separated from norite by a zone of transition rock that consists of irregular layers representing the complete sequence from norite to anorthosite. Contacts with the anorthosite core and with the marginal norite are gradational, and the rocks become more mafic toward the norite and less mafic toward the anorthosite. The irregular alternating layers of noritic and anorthositic rock commonly are lens-like, and hence pinch out laterally. They range in thickness from about 1 foot to as much as 60 feet. Grain size is extremely variable, and the range in crystal lengths is from half an inch to 10 feet. Generally the smaller grains of more uniform size occur in the more mafic phases of the rock, whereas the larger crystals are found in the andesine-rich phases.

The noritic layers commonly exhibit a distinctive poikilitic texture, with subhedral to euhedral crystals of hypersthene enclosing smaller tabular, euhedral crystals of andesine. There is preferred orientation among the andesine crystals that are included within many of the hypersthene crystals. This orientation also exists between the enclosed andesine crystals of adjacent hypersthene units, which are separated from each other by coarse-grained subhedral andesine. The hypersthene units effect a distinct layering by their parallel alignment, and in addition, the orientation of the andesine inclusions is parallel to the alignment of these hypersthene units. The poikilitically included plagioclase remains constant in composition (andesine, An39-46) as the grain size varies. In addition, the composition of the enclosed plagioclase is the same as that of the plagioclase that surrounds the hypersthene host units.

The transition rocks are characterized by the greatest variation in grain size and by the highest degree of euhedralism of the rocks within the complex.

---

* The term "iron-ore minerals," as here used, includes ilmenite, magnetite, and titaniferous magnetite.

Anorthosite. The typical anorthosite is light bluish gray, and has an extremely coarse-grained hypautomorphic texture. Andesine makes up about 97 percent of the rock. Small amounts of interstitial chlorite, biotite, hornblende, and iron-ore minerals are scattered through the rock. All of the plagioclase grains have been thoroughly shattered. Irregular fractures cross grain boundaries, but there is no common relation of fractures from grain to grain. One effect of the shattering is to change the original bluish-gray color of the anorthosite to almost pure white. The shattering, which is present in all rocks of the norite-anorthosite complex, is characterized by an unsystematic arrangement of the fractures and by lack of appreciable relative movement of the fragments. Original grain boundaries are intact, and albite and pericline twin lamellae are sharp and show little bending or dislocation.

Apatite-Ilmenite Rocks. Several large bodies and many small masses of apatite-ilmenite rocks are genetically related to the norite-anorthosite complex. Most of them are in the transition rock, although at least two large bodies are present in the norite, and many small ones crop out in the marginal part of the anorthosite. They are irregular, dike-like or lens-like bodies that are dark reddish-brown to black, medium-grained, and massive except for a few relic structures defined by traces of original layering. Apatite, iron-ore minerals, fibrous hornblende, and chlorite form the mineral assemblage, but many relic grains of hypersthene, andesine, and olivine are also present.

Sequence of Crystallization. The order of crystallization of the magmatic minerals, the deuteric minerals, and the hydrothermal minerals (fig. 2) has been deduced from the gross structural and textural features of the compex (table 1), and from smaller-scale features observed in thin sections. Crystallization during the magmatic stage probably proceeded inward from the margin of the intrusive mass, and the sequence of formation of norite, transition rock, and anorthosite was parallel to the sequence of crystallization of the primary minerals. This is indicated by 1) the change from dominantly xenomorphic textures on the margin to dominantly hypautomorphic textures near the core, 2) the progressive increase in grain size toward the core, 3) the concentration of hypersthene in the marginal norite and to a lesser degree in the transition rock, and 4) the fact that crystallization of hypersthene commenced before crystallization of andesine.

Table 1. Structural and textural criteria for sequence of crystallization in the norite-anorthosite complex.

Norite	Transition rock	Anorthosite
A. STRUCTURAL FEATURES		
1. Areal relations. Borders transition rock on northwest, west, and south. Grades into transition rock.	Borders anorthosite on northwest, west, and south. Grades outward into norite and inward into anorthosite.	Core of intrusive; grades outward into transition rock.
2. Layering. Dips away from transition rock.	Dips away from anorthosite and toward norite.	Not detectable.
B. TEXTURAL FEATURES		
1. Degree of euhedralism. a. Hypersthene. Subhedral to euhedral.	Subhedral to euhedral.	Euhedral.
b. Andesine. Anhedral to subhedral.	Subhedral to euhedral.	Euhedral to subhedral.
2. Grain size. Medium to coarse.	Coarse, becoming coarser toward anorthosite. Very large crystals are common.	Coarse. Very large crystals are common.
3. Texture. Dominantly xenomorphic, becoming hypautomorphic toward transition rock.	Dominantly hypautomorphic. Poikilitic euhedral crystals of hypersthene, enclosing euhedral crystals of andesine, are common.	Dominantly hypautomorphic. Some large poikilitic crystals of hypersthene enclose large crystals of andesine.

As hypersthene and andesine crystallized to form the norite and transition rock, the proportion of pyroxene to plagioclase progressively decreased as crystallization proceeded. Little hypersthene was developed after the transition rock had formed, and only a few local pockets of this mineral are present in the outer parts of the anorthosite proper. Very late in the magmatic stage, after most of the andesine had crystallized, the complex was uniformly shattered. The shattering was followed by development of deuteric minerals at the expense of the magmatic minerals, and hydrothermal minerals were formed still later by alteration of both magmatic and deuteric minerals. The apatite-ilmenite rocks are considered to be the result of hydrothermal replacement of the earlier mafic minerals by the apatite and the iron-ore minerals.

YOUNGER IGNEOUS ROCKS

Biotite quartz diorite occurs along the southern margin of the area, south of the Dillon fault in the San Gabriel fault zone (fig 1). It is light gray and medium to coarse grained. Hypautomorphic texture is predominant, although seriate and porphyritic varieties of the rock are common. The typical quartz diorite consists of about 55 percent of plagioclase (An18-26), 30 percent of quartz, 10 percent of biotite, 1 to 2 percent of microcline, and 1 to 2 percent of minor accessory constituents. Considerable alteration is reflected by development of calcite, sericite, zoisite, epidote, and chlorite.

The members of the norite-anorthosite complex are intimately intruded by muscovite-biotite granite in the northern and northeastern parts of the region. This granite is light pink and medium to coarse grained. The texture generally is hypautomorphic, although the rock is in part so coarse grained that it is pegmatitic. The granite consists typically of 30 percent of microcline, 25 percent of quartz, 15 percent of plagioclase (about An20), 10 percent of orthoclase, 5 percent of perthite, 5 percent of biotite, and 3 to 4 percent of muscovite. Considerable alteration has resulted in development of myrmekite, which makes up about 20 percent of the rock, as well as epidote, sericite, zoisite, and chlorite. Dikes of pegmatite and aplite are associated with the granite.

Lamprophyre dikes are abundant, and intrude both the norite-anorthosite complex and the granite. They range in thickness from 2 feet to about 14 feet. The rock is dark gray, fine to medium grained, and is hypautomorphic in texture. Schistose structure is locally common. Typically the lamprophyre comprises about 35 percent of plagioclase (An49-52), 60 percent of hornblende, small, scattered crystals of apatite and zircon, and sparse grains of ilmenite. Biotite, chlorite, epidote, zoisite, and sphene occur as secondary minerals.

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GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER VIII

MINERAL DEPOSITS AND MINERAL INDUSTRY

1954

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San Francisco — Bulletin 170 — September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER VIII

MINERAL DEPOSITS AND MINERAL INDUSTRY

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Editorial Note:

CHAPTER EIGHT summarizes the occurrence and significant features of mineral deposits in southern California, and relates the utilization of many of these deposits to the remarkable industrial development of the region. It is scarcely surprising that a region of such geologic complexity should offer a wide variety of mineral concentrations for study and exploitation. Metalliferous deposits, most abundant in the desert and other interior parts of southern California, have yielded impressive quantities of iron, tungsten, base metals, precious metals, and rare earths, and represent such geologic processes as sedimentation, contact metamorphism, and hydrothermal mineralization of several types. Even more numerous and more varied are deposits of nonfuel nonmetallic materials—the so-called ''industrial minerals''—which form the backbone of industry in southern California. These occur in all parts of the region, and range from igneous rocks and certain of the minerals in such rocks to large deposits of limestone, sand and gravel, clays, and salines.

The growth of population and industry centering in the Los Angeles area has created tremendous demands for a host of mineral commodities. The attendant growth pattern of mining and processing has been characterized by numerous shifts, many of them sudden and some of them surprising, thanks especially to improvements in knowledge of the mineral deposits, changes in their processing, and the development of wholly new markets. Although the relations between supply and use are never static, many mineral commodities, especially the construction materials, are mined, processed, and marketed wholly within the southern California region. The demands for other materials, such as base metals, bentonite, certain clays, glass sand, and sulfur, far exceed the known available supplies in the region, whereas the supplies of still others, such as boron minerals, diatomite, iodine, rare-earth minerals, and tungsten, are sufficiently great to permit large-scale exports from the region. It seems clear that, for many years to come, southern California deposits will continue to furnish increasing quantities of minerals, especially nonmetallic minerals, to centers of demand both within and outside the region.

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1. SALINES IN SOUTHERN CALIFORNIA

By William E. Ver Planck *

GENERAL FEATURES

Salines include those naturally occurring salts that are normally found in aqueous solutions and in the soluble residues derived from the evaporation of such solutions. Saline commodities of commerce include borates, calcium chloride, bromine, iodine, potassium salts, sodium chloride (common salt), sodium carbonate, and sodium sulfate. Two additional commodities are conveniently included with the salines. Gypsum, although commonly classified as an agricultural and constructional material, is a saline from the geological point of view. Lithium compounds are herein regarded as salines because the most important current source in southern California is the brine of Searles Lake, in the northwestern corner of San Bernardino County.

The value of the saline commodities produced in southern California was more than $37 million in 1950, or about 17 percent of the State's total mineral production exclusive of mineral fuels. About 95 percent of the borates consumed in the entire world is obtained from deposits in the Kramer district of Kern County and from the brine of Searles Lake. Searles Lake also yielded the first significant output of potash from mineral deposits in the United States; although deposits in New Mexico now dominate the American potash industry, Searles Lake still accounts for 5 to 10 percent of the domestic production. This deposit also furnishes 20 to 25 percent of the lithium compounds consumed in this country each year. Domestic iodine requirements are derived almost entirely from certain oil-field brines in the Los Angeles area.

Deposits of other, more widely distributed salines supply important local demands. Searles Lake and Owens Lake provide sodium carbonate for the West Coast. Deposits in eastern Riverside County, western Imperial County, and northwestern Ventura County yield gypsum for use in southern California. Much of the common salt consumed in southern California comes from the Mojave Desert. Bristol Lake, in southeastern San Bernardino County, furnishes the calcium chloride used by the algin industry of San Diego, and also is used as a refrigerant and portland cement additive throughout southern California.

Brines and Their Origin. Dissolved material is to be found in almost all waters, and even the fresh water of rivers contains a few hundred parts per million of dissolved solids. The average salinity of sea water amounts to about 3.5 percent, and some desert basins contain saline lakes whose brine is more than eight times as concentrated as sea water.

Many of the soluble salts are derived from the weathering of rock-forming minerals. Carbon dioxide of the atmosphere dissolves in water to form a weak solution of carbonic acid that slowly attacks silicates and aluminosilicates. Feldspars, for example, are broken down to insoluble clay minerals and to carbonates of potassium, sodium, and calcium that are carried away in solution. Soluble sulfates result from the action of sulfuric acid derived from the weathering of sulfides, particularly pyrite.

The weathering of typical rock-forming minerals does not produce the large quantities of chlorides and borates that are present in some waters. An important part of the sodium chloride in terrestrial waters originates from the connate water of marine sediments. Much of the borates and perhaps part of the chlorides are thought to be derived from hot springs of volcanic origin, or from the leaching of volcanic ejecta.

The most abundant metallic ions in saline waters are sodium, potassium, calcium, and magnesium. Although no two saline waters are exactly alike, they can be divided into three main types on the basis of the predominating acid radical. First is the chloride type, which includes many terrestrial brines as well as sea water. Sea water is essentially an impure solution of sodium chloride, and contains enough chloride ion to combine with all the sodium, the most abundant metallic ion, and part of the magnesium, the next most abundant metallic ion. Terrestrial brines that contain chloride in excess of sodium are comparatively rare, and in such brines calcium is more abundant than magnesium. Most terrestrial brines of the chloride type contain a higher proportion of sulfate than does sea water. There is a complete gradation between the chloride brines and brines of the second type in which sulfate is the predominating acid radical. Similarly, an increase of carbonate leads to the third type, the alkali or volcanic brines. Many alkali brines contain carbonate, sulfate, and borate, and chloride is present in subordinate amounts.

Chloride and sulfate brines are derived from the weathering of sedimentary rocks, whereas alkali brines are characteristic of basins that contain volcanic rocks. Ground-water in areas of granitic rocks is likely to contain only 100 parts or less per million of dissolved solids, mostly calcium carbonate and silica.

---

* Assistant Mining Geologist, California Division of Mines.

The Formation of Saline Minerals. Almost all deposits of saline minerals have been formed by the evaporation of brines. In general, salts crystallize in the inverse order of their solubilities, although the relative proportions of the dissolved solids also are important in controlling the order of deposition. First to be precipitated are slightly soluble calcium carbonate ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$). From sea water and other chloride brines, common salt ($NaCl$) is the next mineral precipitated. If much sulfate is present, however, the crystallization of sodium sulfate may follow that of the slightly soluble calcium salts, especially at low temperatures. Many alkali brines yield trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$) rather than sodium chloride.

The mother liquor from which the salts of moderate solubility have been precipitated is called bittern. Sea-water bittern is rich in the chlorides and sulfates of magnesium, and contains smaller amounts of potassium and bromide. The high magnesium content distinguishes it from bitterns derived from terrestrial chloride brines. Alkali brines yield bitterns containing alkali borates, carbonates, chlorides, and sulfates.

The desiccation of bittern yields highly soluble salts, many of which are complex. Bittern salts of marine origin include the following minerals:

Sylvite	KCl
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$
Kieserite	$MgSO_4 \cdot H_2O$
Polyhalite	$2CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$
Boracite	$6MgO \cdot 8B_2O_3 \cdot MgCl_2$

In contrast, the principal minerals associated with the alkali brine of Searles Lake are:

Halite	$NaCl$
Hanksite	$9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$
Trona	$Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$
Borax	$Na_2B_4O_7 \cdot 10H_2O$
Glaserite	$3K_2SO_4 \cdot Na_2SO_4$

In general, only parts of the ideal, complete series of saline residues are found in nature. Large deposits of pure gypsum and pure salt are well known, but deposits of bittern salts are rare, and commonly are mixtures of several salts.

The undrained basins of the southern California deserts are ideal localities for the accumulation of salts by evaporation of dilute saline waters. Most playas, however, probably contain salines only in the form of thin, efflorescent crusts, or as crystals disseminated in the playa sediments. Commercially significant saline deposits seem to have been formed only in the basins that received the drainage of a large area for a long time. Under favorable circumstances these deposits are covered with impervious mud that protects them from re-solution. Thus the saline deposits of a few Pleistocene lakes are preserved essentially as they were when they were formed several thousand years ago. Salines also occur in older rocks, some of which have been folded and faulted, and even subjected to metamorphism.

SOUTHERN CALIFORNIA LOCALITIES AND OPERATIONS

The occurrence and origin of the complex alkali brines of Searles Lake and Owens Lake, and the commercial recovery of borax, potash, soda ash, and other salines from them are described by Mumford in Contribution No. 2 of this chapter. Chloride and chloride-sulfate brines yield common salt, calcium chloride, and sodium sulfate. Gypsum is the principal saline found in the Tertiary and older rocks of southern California.

Salt From Sea Water. The production of salt by the solar evaporation of sea water is a comparatively small industry in southern California, and is limited in part by lack of suitable land. A large area is required, because the average yield is only about 40 tons of salt per acre. The plants of the Western Salt Company, at the south end of San Diego Bay near Chula Vista and on Newport Bay in Orange County, produce a significant part of the salt that is consumed in southern California.

In the solar evaporation process, sea water is first partially evaporated in a series of outer or concentrating ponds built on the salt marshes. Insoluble matter settles out, calcium carbonate and gypsum precipitate, and the brine is brought to saturation with respect to sodium chloride. Then the saturated brine, or pickle, is run into crystallizing ponds where continuing evaporation causes salt to form. In order to prevent precipitation of the objectionable bittern salts, the crystallizing ponds are periodically drained and refilled with fresh pickle. Once a year the salt is harvested with dragline scrapers and washed with strong brine. The product, crude undried salt, contains about 99.3 percent of NaCl.

Salton Sea. Salton Sea is a shallow body of sodium chloride-sulfate brine whose salinity is roughly that of sea water. It occupies the lowest part of the Imperial Valley, a northwest-trending structural trough that is bounded on the northeast by active branches of the San Andreas fault. The Gulf of California, which occupies the same trough, is separated from the Salton basin by the Colorado River delta. The floor of Salton Sea is a little more than 270 feet below sea level.

The modern Salton Sea was formed in 1905 and 1906, when fresh water from the Colorado River broke into the basin and flowed uncontrolled until February 1907. Prior to the flood, Salton basin was a bare, alluvial plain with a salt-crusted playa at its northwest end. Very recently in terms of geologic time, perhaps within the past 400 years, a body of fresh or at least brackish water called Lake Cahuilla occupied the basin and formed beaches at about the +40-foot contour. Quite possibly Lake Cahuilla was but one of a number of lakes in the basin, each of which was formed by periodic flooding from the Colorado River, and subsequently was reduced by evaporation.

The fresh water of the 1905-1906 flood quickly dissolved the playa salts and formed a sodium chloride brine with a substantial sulfate content. As evaporation reduced the volume of water, the content of dissolved solids increased from 0.35 percent in 1907 to 1.65 percent in 1916 and to about 3.5 percent at the present time. Today the evaporation from the surface of Salton Sea is roughly balanced by inflow, principally in the form of drainage from the irrigation systems of the Imperial and Coachella Valleys.

Salt has been produced from the water of Salton Sea by solar evaporation. The largest plant, the Imperial Salt Works on the southeast shore near Frink station, was productive from 1935 through 1946. Like the sea-water plants, it contained a system of concentrating ponds and crystallizing ponds, but it yielded a sodium sulfate bittern rather than a magnesium-rich bittern. Because of the temperature-solubility relations of sodium sulfate, this salt formed in the crystallizing ponds in preference to sodium chloride at temperatures lower than about 38° F. For this reason, the plant was not operated during the winter season.

Salt Lakes of Southeastern San Bernardino County. Dale Lake, Danby Lake, Cadiz Lake, and Bristol Lake, in southeastern San Bernardino County, are dry lakes that contain saline minerals associated with concentrated chloride brines of the terrestrial type. Chemically these deposits form a series ranging from the sodium chloride-sulfate association of Dale Lake to the uncommon sodium-calcium chloride association of Bristol Lake.

Dale Lake occupies a basin 28 miles south of Amboy and 23 miles east of Twentynine Palms. Borings about 250 feet deep within an area of a square mile have disclosed a series of lenticular beds of halite and thenardite (Na_2SO_4) separated by impervious clay. Some lenses are nearly pure halite and others are nearly pure thenardite, but most of the lenses are mixtures of these minerals. The saline beds are permeated with concentrated brine that contains 20 to 22 percent of sodium chloride and 7.5 to 8 percent of sodium sulfate. Up to the end of 1948 sodium sulfate and sodium chloride were produced from brine pumped from wells. Chilling of the brine, effected by spraying in winter, caused the crystallization of mirabilite ($Na_2SO_4 \cdot 10H_2O$), which then was converted to anhydrous sodium sulfate. Sodium chloride was produced from the sulfate-free tail liquor by solar evaporation.

Danby Lake, 30 miles southeast of Cadiz, lies in a structural trough between the Iron Mountains and the Old Woman Mountains. Lenticular bodies of nearly pure rock salt, some of which are more than 2 square miles in area and as much as 10 feet thick, lie close to the surface. Some of the salt bodies are porous, and are permeated with saturated sodium chloride brine that contains sulfate in minor amounts. In addition, crystals of halite, mirabilite, and the selenite variety of gypsum are disseminated through the impervious clays that enclose the bodies of rock salt. These minerals also form lenticular concentrations in which crystals constitute as much as 90 percent of the mass. Salt was quarried late in the nineteenth century by the Crystal Salt Company, and at that time salt blocks were used to build a house on the property. This house remained standing until World War II, or for a period of at least 50 years. Salt again was produced from 1934 to 1942, and more recently the Metropolitan Water District of southern California completed an exploration program that included solar evaporation tests on the brine.

Cadiz Lake and Bristol Lake occupy the Bristol Basin south and southeast of Amboy. Both lakes contain sodium-calcium chloride brines that are substantially free from sulfate. H. S. Gale has postulated that this unusual concentration of chloride originated from the volcanism that developed the Bagdad or Amboy Crater, which lies on the west margin of Bristol Lake.

Cadiz Lake is the least well known of the four major saline lakes in southeastern San Bernardino County, and has yielded no commercial production. Beds of gypsum and salt have been reported, and a few analyses indicate that, although the brine contains calcium chloride, this salt constitutes a relatively low percentage of the dissolved solids.

Bristol Lake contains, in its central part, a series of rocksalt and clay beds at least 1,000 feet thick. The uppermost salt bed is three feet or more thick over an area of five square miles. These sediments yield meager flows of saturated brine composed of roughly equal parts of sodium chloride and calcium chloride. Although sulfates are absent from the central part of the lake, crystals of the selenite variety of gypsum are abundantly distributed through the marginal clays, and actually supplied a plaster mill at Amboy from 1906 to 1924. For many years the California Salt Company and its predecessors have quarried salt from the uppermost bed of rock salt. This company and the National Chloride Company of America also collect the calcium chloride brine in long trenches or pits sunk through the upper salt bed. The brine is transferred to solar concentrating ponds, where the sodium chloride that it contains is crystallized out. Much

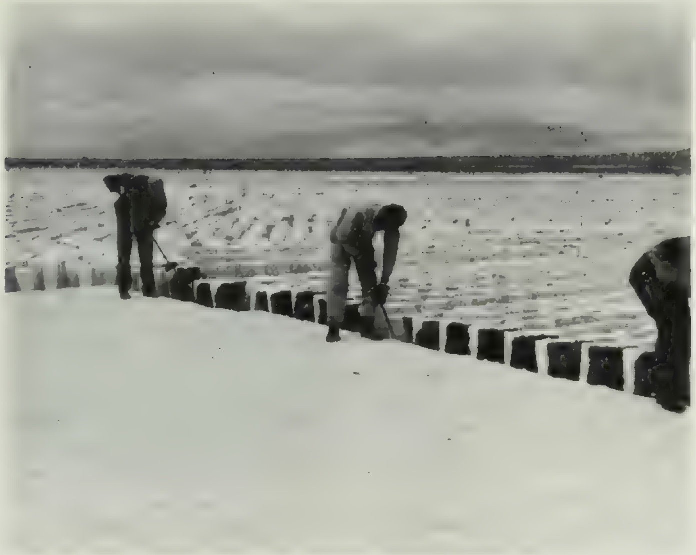

FIGURE 1. Harvesting salt from the surface of Koehn (Kane) Lake, near Saltdale.

of the residual liquor is marketed as liquid calcium chloride without further treatment, and a portion is further dehydrated by boiling to produce flake calcium chloride.

Koehn (Kane) Lake. Koehn (Kane) Lake is a playa in eastern Kern County, about 30 miles northeast of Mojave, that yields salt, although neither saline beds nor subsurface brines are known. In most winters rainfall is sufficient to form a thin sheet of water on the playa surface. This water dissolves the efflorescent, salty crust that covers the clay surface in the central part of the playa. When it has been reduced nearly to the saturation point by evaporation, the surface brine is run into solar crystallizing ponds where nearly pure salt forms. Concentrating ponds are not required, and the salt is harvested directly (fig. 1).

Gypsite, an unconsolidated, earthy mixture of gypsum and clay, is present on the south margin of the lake. The deposits are lenticular bodies about 5 feet thick that lie beneath one to two feet of grass-covered soil, and probably were formed by the evaporation of upward migrating water containing calcium sulfate. Material with a minimum of 60 percent $CaSO_4 \cdot 2H_2O$ is mined for use as an agricultural mineral.

A small amount of ulexite ($CaNaB_5O_9 \cdot 8H_2O$) has been produced from the west margin of the lake, near Gypsite. It occurs in the form of "cotton balls" as much as 3 inches in diameter. Like the gypsite, it is derived from the evaporation of upward-migrating solutions.

Iodine Brines. The entire domestic production of iodine is derived from oil-field brines near Dominguez Hill, Seal Beach, Venice, and Inglewood in the Los Angeles area. The only similar occurrence of iodine known in the United States is in Louisiana. The California brines contain only 2½ to 3 percent of dissolved solids, almost entirely sodium chloride. Iodine, in amounts up to 140 parts per million, is thought to be present as sodium iodide. The source of the iodine is obscure, but it may have been derived from sea water in some way. Sea water contains only traces of iodine, but this element is present in some marine plants and animals, and particularly in certain types of kelp.

Iodine is recovered from the water that accompanies the oil pumped from the wells. This water, with its content of residual oil, is an objectionable waste that could not be discarded in a metropolitan area without some cleaning treatment. Cleaning of the water also is an important preliminary step in the recovery of iodine, and thus accomplishes two purposes. Two processes are used to produce the iodine. The Dow Chemical Company liberates iodine from the clarified water by means of chlorine, while the Deepwater Chemical Company accomplishes the same objective by means of silver nitrate.

PRE-PLEISTOCENE SALINE DEPOSITS

Numerous deposits of saline minerals in southern California clearly were formed in Tertiary playas that must have been not greatly different from the Pleistocene lakes described in the preceding paragraphs. These bedded deposits have been more or less folded and faulted, and the mother liquors from which the salines crystallized have been drained away. In some deposits the saline minerals have undergone no great change, but in others they have been altered by leaching or by heat and pressure. The Tertiary borate deposits, described by Mumford in the following paper, are among those in which alteration has occurred.

Thenardite Deposits of the Durmid Hills. Thenardite (Na_2SO_4) occurs in the Durmid Hills on the northeast shore of Salton Sea, 1 to 1½ miles east of Bertram and not far south of the boundary between Riverside and Imperial Counties. The associated sediments are moderately folded shaly and silty beds of Tertiary age that trend west-northwest and dip from 60° to vertical. Interbedded with the shale is hard, gray gypsum in beds 1 to 2 inches thick, and the shale also is cut by veinlets of secondary gypsum.

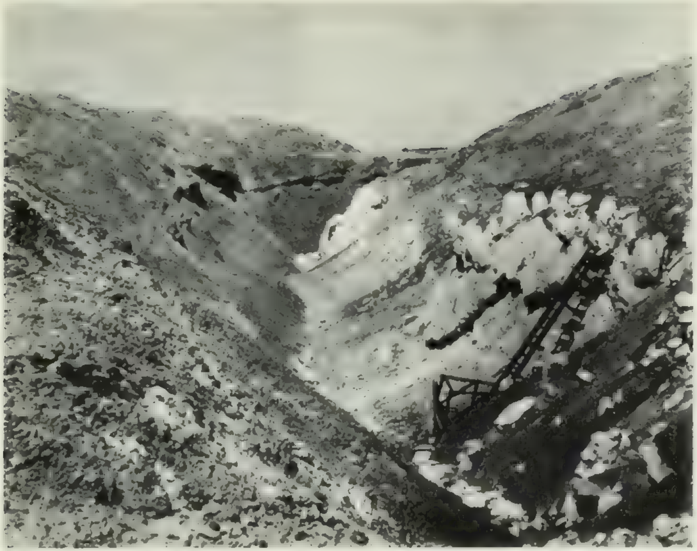

FIGURE 2. Main open cut in deposit of thenardite, Durmid Hills near Bertram.

Thenardite forms individual beds as much as 5 feet thick. These are exposed for a distance of about 3,000 feet along the strike. Some bloedite ($MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$) is associated with the thenardite, and the magnesium content of the beds may well increase with depth. Several attempts have been made to quarry thenardite (fig. 2), but the most recent operation was abandoned because the magnesium content of the material was higher than anticipated.

Avawatz Mountains Deposits. Salt and associated gypsum occur in highly deformed Tertiary lake beds in the northern foothills of the Avawatz Mountains, San Bernardino County. The structure is complex, and the stratigraphic relations have not yet been deciphered. Two nearly parallel strips of lake beds, separated and bounded by strips of chaotic breccias, are exposed in a northwest-trending belt 9 miles long. The strips dip in general steeply south. The lake beds are probably of late Miocene or early Pliocene age. Overlying both lake beds and breccias is the gently folded Funeral fanglomerate, of late Pliocene or early Pleistocene age.

The lake beds have been divided into four units. One of these consists of sedimentary breccias and conglomerates, and a second comprises 100 to 600 feet of predominantly red shales, clays, and fine, thin-bedded sands with interbedded rock salt. The salt-bearing beds grade into a third unit, 600 to 800 feet of predominantly light-tan colored, gypsum-bearing shale and sandstone. The gypsum occurs as relatively thin beds associated with greenish, gypsiferous clay, and forms a small fraction to as much as two thirds of the total thickness. The fourth unit comprises nearly 1,000 feet of non-gypsiferous sediments into which the gypsiferous unit grades.

Although the complexity of the structure makes it difficult to determine the geologic history of the deposits, the salines probably represent one or more lakes that were formed on a relatively flat surface underlain by chaotic breccias. The precipitation of salines seems to have occurred during two distinct periods that were separated by an interval when only clastic sediments were laid down. Salt-precipitating conditions prevailed during the first period, and gypsum was formed during the second.

Only the Boston-Valley claims, in the southern strip of lake beds between Denning Spring Wash and Cave Spring Wash, have been thoroughly explored. Diamond drilling has shown that an area of less than two acres contains 1,300,000 tons of salt of greater than 92 percent purity. Little gypsum occurs in this area.

The gypsum and salt beds also are exposed in other areas. Salt Basin, in the northern strip of lake beds east of Cave Spring Wash, is a valley trough formed by the leaching of the salt beds that crop out beneath its floor. From a distance the reddish salt beds contrast strongly with the tan-colored gypsiferous beds that adjoin them on the south. Farther east the salt and gypsum beds are again exposed on the Jumbo claims, and in Sheep Creek, near the east end of the strips of lake sediments, contorted gypsum-bearing beds are in fault contact with breccia. Big Gypsum or Kelley Hill is a conspicuous exposure of gypsum on the northwest side of Denning Spring Wash, in the northern strip of lake sediments. The westernmost exposures are some hills known as the Celestite Hills or West End, where the gypsum-bearing beds are folded into two or more domal anticlines.

TERTIARY GYPSUM DEPOSITS

Gypsum is the most common saline mineral found in the Tertiary deposits. The gypsum itself is massive, fine- to medium-grained, and ranges from nearly pure, translucent alabaster through opaque, white to dark rock gypsum of 90 percent or higher grade to gypsiferous clay and sand. Typically it is enclosed in folded bodies of silt and clay that are similar to the mechanically deposited sediments of the Pleistocene lakes. Probably the gypsum was precipitated from saline waters in the same way that sodium chloride and sodium sulfate are formed, and as gypsum is known to precipitate in the concentrating ponds of solar salt works.

The Tertiary gypsum deposits range from thin, discontinuous beds, like those associated with thenardite in the Durmid Hills, to massive bodies that amount to many thousands of tons. In the Death Valley area, the Furnace Creek formation contains playa sediments that interfinger with more abundant lava flows and tuff beds. Although this formation is best known for its borate deposits, it also contains beds of gypsum. At China Ranch similar lake beds, probably of Pliocene age, contain 20 feet of gypsum. In the upper Cuyama Valley, gypsum deposits of substantial size occur in clay beds that are associated with a great thickness of coarse, nonmarine sediments of Miocene age. The largest known gypsum deposit in California is in nonmarine Miocene sediments in the Fish Creek Mountains, Imperial County.

Quatal Canyon Deposit. The Quatal Canyon gypsum deposit is east of Ventucopa in the upper Cuyama Valley of northwestern Ventura County. A gypsum bed 10 to 30 feet thick occurs in the Quatal red clay, a nonmarine facies of the upper Miocene Santa Margarita formation. Underlying this clay are the middle Miocene Caliente red beds. These nonmarine rocks grade northwestward into marine sediments, and it seems likely that the gypsum was formed in a temporary lake near the shore of an inland sea. In Quatal Canyon the gypsum forms a near dip slope on the southwest flank of one of a series of open, northwest-trending anticlines. Here the Monolith Portland Cement Company quarries gypsum for use as a retarder in the manufacture of portland cement at its plant in Tehachapi (fig. 3).

Fish Creek Mountains Deposit. The largest known gypsum deposit in the State is near the northwest end of the Fish Creek Mountains, about 30 miles west of Brawley and near the western boundary of Imperial County. The gypsum occurs in the nonmarine Split Mountain formation of Miocene age. This formation, which lies with depositional contact on a "basement" of igneous and metamorphic rocks, is a very coarse conglomerate with angular boulders as much as 10 feet in diameter, and with subordinate lenses of unconsolidated, gray, arkosic sand that are especially abundant in the upper part of the section. Gypsum, at least 100 feet thick and almost entirely free from impurities, forms the uppermost unit of the sequence, and is separated by a comparatively small thickness of sand from overlying sandstone and shale of the marine Imperial formation.

In contrast with the Quatal Canyon deposit and most of the other Tertiary deposits, few fine-grained sediments are associated with the Fish Creek Mountains gypsum. Arkosic sand, rather than clay, lies immediately above and below the gypsum, and in places only an inch or two of arkose separates the gypsum from boulder conglomerate. Perhaps the gypsum was precipitated from saline waters in a structural basin that was partially filled with detrital material from the surrounding highlands. The absence of clastic impurities from the gypsum suggests that the deposits accumulated very rapidly as compared with the formation of the detrital deposits.

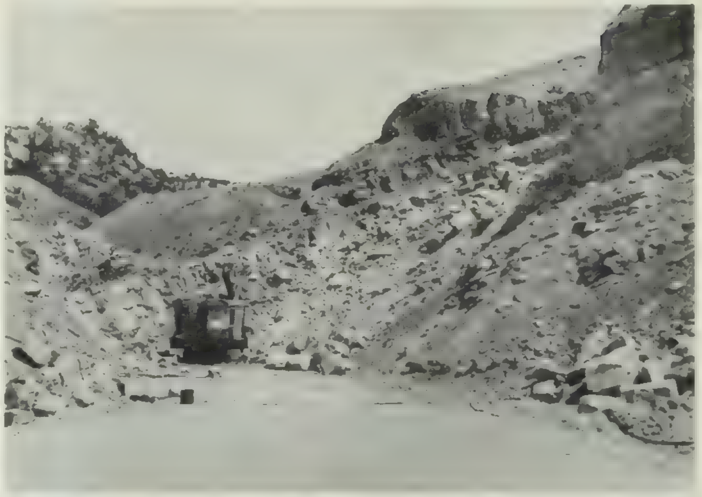

FIGURE 3. Gypsum quarry of the Monolith Portland Cement Company in Quatal Canyon, Cuyama Valley.

The Tertiary rocks have been partially removed by erosion in the Fish Creek Mountains area. They have been preserved, however, in a shallow synclinal basin that is occupied by a wash immediately west of the low northwest end of the mountains. Above the level of the wash the Imperial formation has been largely removed, and gypsum is exposed on the hills bordering the wash in the form of a blanket that dips toward the synclinal axis. Other large remnants of the original deposit exist in less accessible areas to the south and west.

Anhydrite ($CaSO_4$) is exposed where quarrying has opened the gypsum deposit in depth. At points about 120 feet beneath the surface, a zone is encountered where gypsum grades downward into anhydrite. Much evidence indicates that gypsum is the stable phase of calcium sulfate at the surface of the ground, and that calcium sulfate occurs as anhydrite at depths of more than a few hundred feet. Although it has been postulated that anhydrite can precipitate

Table 1. Brines of southern California.

Constituent	Percent of the dissolved constituents								
	Seawater (1)	Salton Sea (1907) (2)	Salton Sea (1916) (3)	Dale Lake (4)	Danby Lake (5)	Cadiz Lake (6)	Bristol Lake (7)	Iodine brine (8)	Searles Lake (9)
Cl	55.292	46.44	49.2	44.7	44.17	60.82	61.95	58.4	38.51
Br	0.188	----	----	----	----	----	--	*	0.25
I	----	----	----	----	----	----	----	0.2	0.003
SO_4	7.692	14.21	13.0	15.8	4.94	0.38	0.08	minus 0.1	13.21
B_4O_7	----	----	----	Tr.	----	----	0.01	----	3.66
HCO_3	----	----	----	----	----	----	----	3.0	----
CO_3	0.207	2.06	0.7	Tr.	Tr.	----	----	----	7.90
Li	----	----	----	----	----	----	----	----	0.02
Na	30.593	28.54	33.0	36.7	50.73	30.71	20.55	36.1	28.72
K	1.106	3.81	0.4	0.02	----	1.41	1.18	----	7.73
Ca	1.197	2.72	1.9	----	0.12	6.12	15.51	1.3	----
Mg	3.725	1.72	1.7	----	0.04	0.56	0.38	0.8	----
Sr	----	----	----	----	----	----	0.08	----	----
R_2O_3	----	0.01	Tr.	----	----	----	----	minus 0.1	----
SiO_2	----	0.48	0.1	----	----	----	----	0.2	----
Misc. and organic	----	----	----	2.7	----	----	----	----	----
Salinity, PPM	35,000 ±	3.934	16,472	----	271,200	73,600	279,149	26,072	344,431
Salinity, grams/liter	----	----	----	298.00	----	----	----	----	----

* Bromine not determined, but is approximately twice the iodine content.

(1) Sea water, mean of 77 analyses. Clarke, F. W., 1924, The data of geochemistry: U. S. Geol. Survey Bull. 770, p. 127, analysis A.

(2) Salton Sea, 1907. Clarke, F. W., 1924, the composition of the river and lake waters of the United States: U. S. Geol. Survey Prof. Paper 135, p. 132, analysis 1.

(3) Salton Sea, 1916. Recalculated from Brown, J. S., 1923, The Salton Sea region, California: U. S. Geol. Survey Water-Supply Paper 497, p. 282, analysis 44.

(4) Dale Lake. Recalculated from King, C. R., 1948, Soda ash and saltcake in California: California Jour. Mines and Geology, vol. 44, p. 190, Table 1.

(5) Danby Lake, test well in sec. 22, T. 2 N., R. 17 E., SB. Analysis furnished by Metropolitan Water District of southern California.

(6) Cadiz Lake. Gale, H. S., and Hicks, W. B., 1920, Potash: U. S. Geol. Survey, Min. Res. U. S., 1917, vol. 2, p. 418.

(7) Bristol Lake, sample from "canal" of National Chloride Company of America. Recalculated from Durrell, Cordell, 1953, Celestite deposits at Bristol Dry Lake, San Bernardino County, California: California Div. Mines Special Rept. 32, p. 13, analysis II

(8) Iodine brine. Recalculated from Sawyer, F. G., and others, 1949, Iodine from oil well brines: Ind. and Eng. Chemistry, vol. 41, p. 1550, Table III, brine D.

(9) Searles Lake, upper structure brine. Recalculated from Ryan, J. E., Industrial salts: production at Searles Lake: Am. Inst. Min. Met. Eng. Trans., vol. 190, p. 449, Table I

directly from saline water, it seems more likely that most anhydrite is an alteration product of gypsum that has been deeply buried.

A large quarry in the Fish Creek Mountains furnishes gypsum for the United States Gypsum Company's plaster plant at Plaster City, about 25 miles to the south. Here are manufactured wall plaster, gypsumboard products, and special plasters for ceramic molds, foundry patterns, dental and orthopedic use, and other industrial purposes.

PRE-TERTIARY GYPSUM DEPOSITS

Pre-Tertiary saline deposits are represented in California by a group of gypsum deposits in eastern Riverside County that are associated with crystalline limestone, quartzite, and quartz-albite-mica schist. They are best known in the Little Maria Mountains near Midland, but similar deposits occur in the Maria Mountains immediately to the east, in the Riverside Mountains to the northeast, and in the Palen Mountains to the northwest. In the Maria Mountains the gypsum-bearing rocks have been termed the Maria formation, and their age has been determined from crinoid remains to be post-Cambrian Paleozoic. Possibly, however, the Maria formation is the metamorphosed equivalent of the gypsum-bearing Kaibab or Moenkopi formations of Clark County, Nevada.

Little Maria Mountains Deposit. In the Little Maria Mountains the gypsum-bearing Maria formation occupies a low pass that crosses the range near Midland. Southward to the end of the range lie granite and gneiss, and granitic rocks extend northward for about two miles. The Maria formation here consists of crystalline limestone, quartzite, and green, schistose, feldspathic quartzite that strike N. 70° E., across the range, and dip 50° to 80° NW. Gypsum and other rocks are interbedded with limestone in zones that are as much as 100 feet thick and have known strike lengths of several thousand yards. Gypsum also forms lenticular bodies in the green schistose rock (fig. 4).

The occurrence of gypsum is much the same in both of these associations. Commonly less than half of a given gypsum body actually

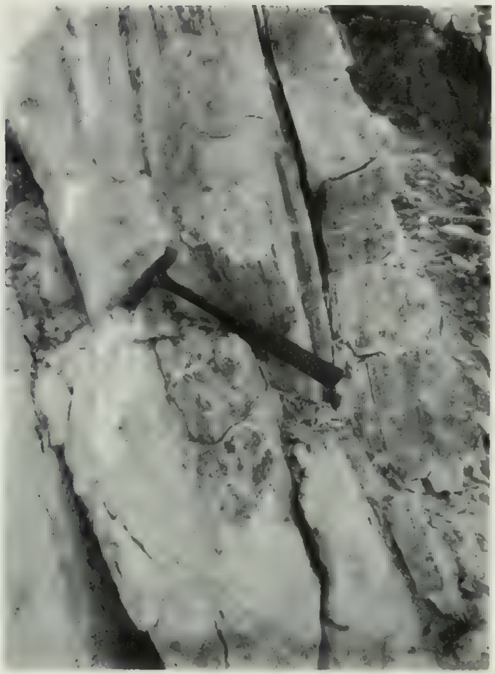

Figure 4. White gypsum and green schistose feldspathic quartzite at mine of the American Gypsum Company, Little Maria Mountains.

is bedded gypsum. The beds in some deposits are 5 to 10 feet thick, but in most they are a foot thick or less. Other materials that commonly are present include green schistose rock, quartzite, and tremolitic limestone. The gypsum itself is a coarse-grained aggregate of flaky, transparent crystals. Although some thick beds of pure gypsum do occur, they grade into gypsiferous schist and gypsiferous limestone. In depth the gypsum grades into coarse-grained anhydrite.

Perhaps the outstanding differences between the Tertiary gypsum deposits and those of pre-Tertiary age are in the nature of the associated sediments. The Tertiary deposits were formed in saline lakes that existed in regions of erosion and subaerial sedimentation, whereas the pre-Tertiary deposits are associated with sediments that were laid down under marine conditions.

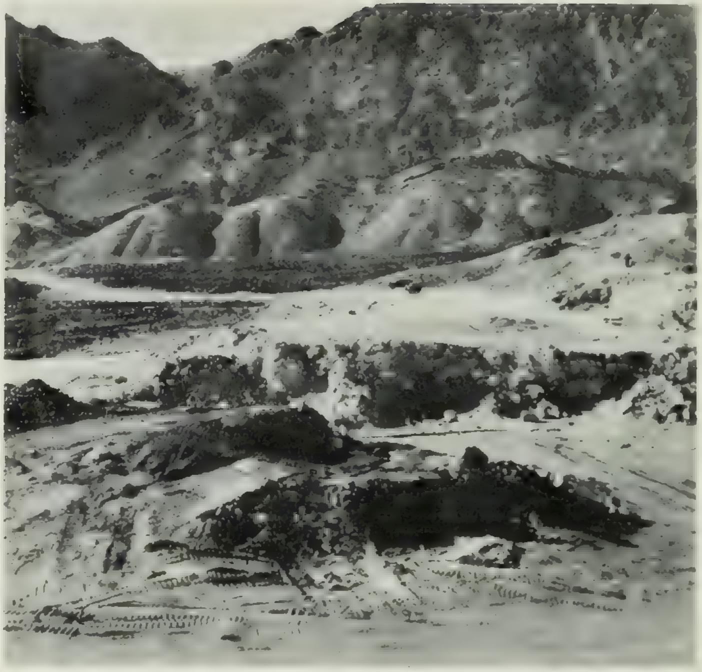

Figure 5. Mine of the Utah Construction Company, Little Maria Mountains; view northwest. Main ridge in background is limestone, and relatively smooth lower slopes are underlain by quartzite.

The United States Gypsum Company manufactures gypsum products at Midland. Raw gypsum has been obtained both from open pits (fig. 5) and from underground mines.

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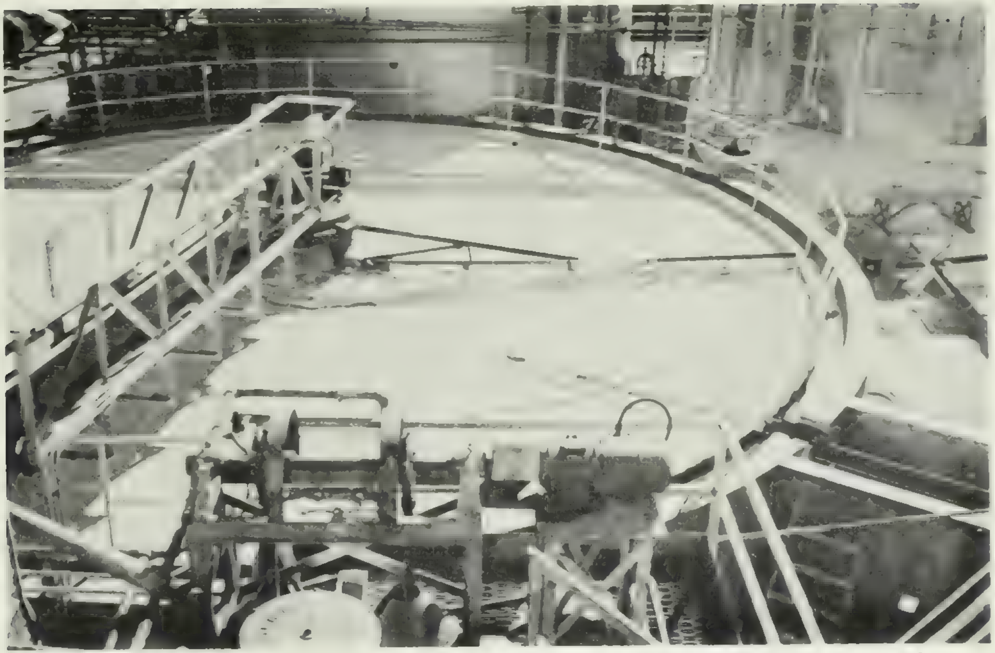

FIGURE 6. Skimming off sodium-lithium phosphate in plant of American Potash and Chemical Co. at Searles Lake, San Bernardino County. *Photo by Walter W. Bradley.*

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2. DEPOSITS OF SALINE MINERALS IN SOUTHERN CALIFORNIA

By Russell W. Mumford[*]

Salines are the naturally occurring salts that are formed by precipitation from the brines of inland lakes or from sea water. Salines from sea water are not as important economically in southern California as they are in the San Francisco Bay area, because little marshy land is available along the sea coast for use as evaporating ponds.

Discussion in this paper will be confined to deposits containing chlorides, sulfates, carbonates, bicarbonates, and borates of sodium, potassium, calcium, magnesium, and lithium, either singly or in combination. Some of the salines occur in brines, and others as solid minerals. Some of the minerals are simple salts such as sodium chloride or borax, but others are double or triple salts. All of these deposits are scientifically very interesting, but not all are of economic interest at the present time. The most important accumulations of salines are located in the Mojave Desert region, as indicated on the accompanying map (fig. 1).

About 1,750,000 tons of salines, valued at about $40,000,000, is being produced annually from Searles Lake, Owens Lake, the Kramer borate district, and Bristol Lake. From Owens Lake come soda ash and sodium sesquicarbonate. From Searles Lake every year are produced chemicals including common salt, chloride and sulfate of potash, salt cake, soda ash, borax, boric acid, and bromine. It also is worthy of note that Searles Lake is a major domestic source of lithium salts. At Boron, in the Kramer borate district halfway between Mojave and Barstow, large quantities of sodium borate ore are produced. This ore is concentrated at Boron or is shipped to refineries at Wilmington, California, and elsewhere, where it serves as a source of borax, boric acid, and other refined boron chemicals.

Ores and brines containing sodium borate now are the major source of the boron products of commerce. Considerably more than 95 percent of the world's supply is produced from the Kramer borate district and Searles Lake, and nothing like these deposits is known elsewhere. Significant quantities of common salt and calcium chloride are produced from Bristol Lake, at Amboy on the Santa Fe Railroad. Saline products from the Mojave Desert are tremendously important to the industry of California, the United States, and the World.

Owens Lake. It is generally agreed that, during the Pleistocene epoch, lakes occupied large parts of Owens, Searles, Panamint, and Death Valleys. The waters from these lakes, which at one time were connected, have long since evaporated; and present surface levels of their deposits are about as follows:

Basin	*Elevation*
Owens Lake	3550 feet
Searles Lake	1616 feet
Panamint Valley	1046 feet
Death Valley	minus 280 feet

Waters that formerly filled Owens Valley overflowed into Indian Wells Valley, and thence into Searles and Panamint Valleys, in each of which there was an extensive lake (see Blackwelder, Contribution 5, Chapter V). The fact that the Searles basin for a time overflowed into Panamint Valley, and that the Panamint lake probably overflowed similarly into Death Valley, evidently did not prevent the accumulation and deposition in the Searles basin of an immense mass of brine and crystalline salts. It is quite apparent that Searles Lake was, for a considerable period of time, the end of the chain of connected lakes. The enormous volume of water required to account for the large bodies of salts deposited from the evaporating lakes in Owens and Searles Lakes probably was derived in part from melting glaciers in the Sierra Nevada. This water, as it ran off from the Sierra Nevada, carried dissolved mineral matter that contributed to the present salt deposits, and possibly this was augmented by contributions from springs and other sources. Alternating periods of greater water flows and desiccation are indicated by layers of clay in the saline deposits at Searles Lake.

Owens Lake is a closed basin at the southern end of Owens Valley and hence lies east of the Sierra Nevada and west of the Coso and Inyo Mountains. It is in the Basin Range province. The rocks to the west are predominantly igneous, and those to the east include both igneous and sedimentary types. The brine of Owens Lake contains carbonates, bicarbonates, sulfates, chlorides, and borates of sodium and potassium.

Precipitation in the Sierra Nevada is much greater than in the Inyo and White Mountains to the east. The area has been one of extensive glaciation, believed to have occurred through at least two major episodes of Quaternary time. The earlier of these was much more extensive than the later. Volcanic activity was widespread during parts of late Tertiary and early Quaternary time, and at present volcanism is expressed by the steam fumaroles at Hot Creek and Coso Hot Springs.

At some time, calculated by Hoyt S. Gale to have been approximately 4,000 years ago, Owens Lake became separated from the rest of the lake system, and thus became a closed basin in which the salts

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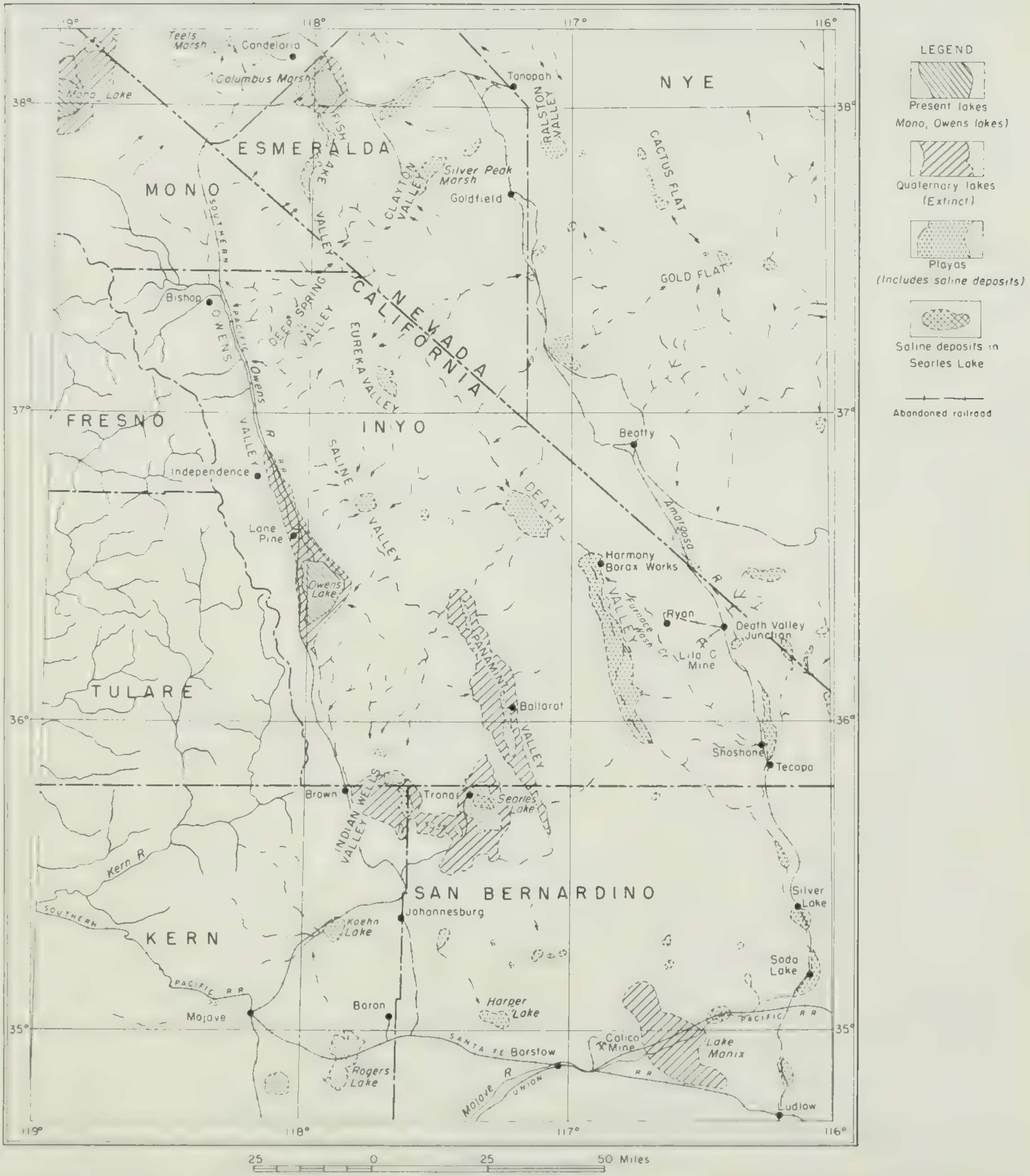

FIGURE 1. Index map of Mojave Desert region, showing location of principal saline deposits. *Modified from U. S. Geological Survey.*

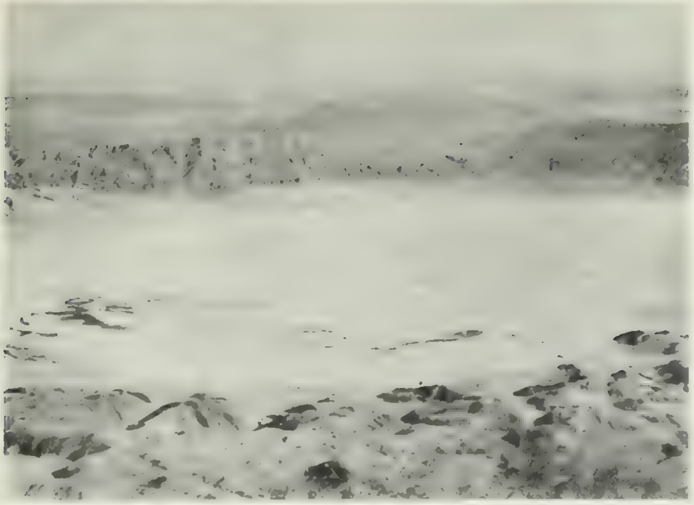

FIGURE 2. Aerial view of Searles Lake, direction southeast. Trona is at near margin of lake at left. *Photo courtesy American Potash and Chemical Corporation.*

began to accumulate. Old beach deposits indicate that the lake at one time was 220 feet higher than it was in 1912, and that it once occupied an area of 240 square miles. About 1920, the City of Los Angeles completed its program of gathering Owens Valley water into its aqueduct, and since that time the lake has receded until only a small pool of brine now appears at the surface opposite Cottonwood Creek. A fairly extensive but thin bed of crystals has resulted from this desiccation. The waters of the lake fluctuate in composition, owing to changes in temperature and run-off. The lake basin has been estimated to contain about 160,000,000 tons of salts.

Since 1904, five plants have been constructed at Owens Lake for the manufacture of soda ash or sesquicarbonate, and one plant for the manufacture of caustic soda. The latest plant was built during World War II. With the exception of the Columbia Southern Chemical Corporation plant at Bartlett, all of the alkali operations at Owens Lake have been discontinued. Somewhat more than 1,000,000 tons of alkali and about 30,000 tons of borax have been produced during the operations of all the plants.

Searles Lake. Searles Lake is a dry-lake basin superficially like many other desert basins in the arid region of the southwestern United States (fig. 2). It is situated in the extreme northwest corner of San Bernardino County, 170 miles north and east of Los Angeles, and its surface lies at an elevation of 1616 feet above sea level. The valley in which the lake is located is about 40 miles long and 25 miles wide.

During the Pleistocene epoch the basin was occupied at least once by a deep lake whose traces are still so distinct as to be indisputable. When the water level was at its highest position, Searles basin was flooded to a depth of 635 to 640 feet above the level of the present body of crystalline salts, and the lake extended back through Salt Wells Valley to join with a broad, shallow lake that flooded much of Indian Wells Valley. With subsequent lowering of the water level, a divide emerged between Indian Wells Valley and Salt Wells Valley, and for a time there was an overflow from Indian Wells Valley to the lower waters in the Searles basin. These events are attested by the records of ancient shore lines and water channels. Horizontal beaches and shore markings over the more rocky parts of the marginal slopes show with great distinctness around the present valley. The old shore lines are marked in many places by deposits of calcareous tufa, some of which form masses of great size. Apparently the highest level of water in Searles Lake was about 2,262 feet above sea level.

The overflow undoubtedly ceased abruptly with the cutting off of the main water supply from Owens Valley. From that time on, evaporation must have proceeded almost without interruption until conditions somewhat like those of the present were established.

Searles Lake contains, in its central portion, a large mass of crystalline salts about 30 square miles in area. An upper crystal body is about 70 or 80 feet in average thickness, and contains about 40 percent of voids that are permeated by a saturated brine. This brine is the raw material for the operations of the main plants of the American Potash and Chemical Corporation and the Westend Chemical Company. The level of the brine stands close to the surface at all times, and varies from about 10 inches above to about 10 inches below the surface.

The upper crystal body is underlain by an impervious seam of clay or mud that is approximately 12 feet in average thickness. Underlying this clay seam is another crystal body, about 35 feet in thickness, that contains a second brine.

According to W. A. Gale, it appears probable that the upper crystal body was deposited following the close of the Tioga, or latest stage, of the Pleistocene glaciation. The mud seam was probably deposited by flood waters during Tioga time. The salt body below the clay seam represents the period of desiccation following the Tahoe, or next-to-last, episode of glaciation.

The run-off waters from Owens Valley during the Tahoe and Tioga stages were heavily laden with sodium and potassium chlo-

Analyses of brines from Searles Lake.

Constituent	*Percent in upper brine*	*Percent in lower brine*
KCl	4.9	2.94
$Na_2B_4O_7 \cdot 10H_2O$	3.0	3.71
Na_2CO_3	4.7	6.78
Na_2SO_4	6.8	6.56
NaCl	16.2	15.51
Others	0.3	0.50
Total salts	35.9	36.00
Water	64.1	64.00
Specific gravity	1.3	1.3

rides, sulfates, carbonates, and borates, and in addition, contained numerous minor constituents. These waters were trapped in Searles Lake and were replenished until overflow ceased from Owens Lake. Thanks to evaporation of the waters, many millions of tons of salts were deposited in the Searles basin.

The mud seams contain considerable organic matter that appears to have been derived mainly from the red pigment of chromogenic bacteria like those that infest the surface of the deposit. This material is resinous in nature, and is insoluble in water but soluble in organic solvents such as alcohol and acetone. It can be extracted from the dried mud in fairly concentrated form, and provides a means for determining the age of the deposit, now that the age of solid organic matter as much as 30,000 years old can be determined by newly developed methods.

The element carbon present in the carbon dioxide of the atmosphere contains an extremely small proportion of the radioactive isotope C-14. This radioactive carbon is disintegrating slowly. However, the ratio of C-14 to total carbon of atmospheric CO_2 is held constant by the cosmic ray bombardment of nitrogen atoms to form new C-14 atoms. Vegetable life obtains its supply of carbon for the building of tissue from atmospheric CO_2, and animals derive their carbon from vegetation. Thus all living tissue contains C-14 in the same ratio to total carbon as that of atmospheric CO_2, but the percentage of C-14 in buried organic material is less by amounts corresponding to the period of burial.

The half-life of C-14 is 5,568 plus or minus 30 years. That is, for a given sample of buried carbon originally derived from atmospheric CO_2, one-half of the original C-14 content will remain at the end of 5,568 years, $\frac{1}{4}$ will remain after 11,136 years, $\frac{1}{8}$ will remain after 16,704 years, $\frac{1}{16}$ after 22,272 years, and so on. Thus a determination of the degree of radioactivity of the carbon content of any organic material will establish its age up to the present limit of the method of measurement.

A sample of organic matter extracted from the bottom of the mud seam between the two salt bodies of Searles Lake has shown an age of something more than 16,000 years, which we may take as the start of the period of flood waters present during Tioga time. The maximum advance of the last continental ice sheet, farther east in the United States, has been established fairly definitely by the work of Dr. W. F. Libby, who used the C-14 method, as having taken place 11,000 plus or minus 100 years ago.

The accumulation of salts in Owens Lake since cessation of the last overflow was estimated by the late Hoyt S. Gale (1914) to have required about 4,000 years. Therefore the melting of the glaciers in the upper Owens Valley drainage probably occurred between 4,000 and 11,000 years ago. Geologists have noted other evidence that suggests the existence of a period of very warm, dry climatic conditions for possibly 2,000 years immediately following the period of latest glaciation. During this period there may have been very little, if any, flow of water into Owens Lake. If this were so, it would set the end of the Tioga stage back to about 6,000 years ago.

The crystalline bodies of Searles Lake contain about twenty minerals. Among those of present economic importance are the following:

Halite	NaCl
Trona	$Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$
Tincal (Borax)	$Na_2B_4O_7 \cdot 10H_2O$
Hanksite	$9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$
Glaserite	$3K_2SO_4 \cdot Na_2SO_4$
Burkeite	$Na_2CO_3 \cdot 2Na_2SO_4$

The plant of the American Potash and Chemical Corporation has been in operation since 1916, when earlier development work was completed. The Trona process is fundamentally one of evaporation of the brine for elimination of water, followed by fractional crystallization of the constituent chemicals. The process in its present form is an outstanding example of the application of physical-chemical research to methods of operation. The end products are potash salts, borax, boric acid, soda ash, salt cake, bromine, and lithium carbonate for industry and agriculture. This company and the Westend Chemical Company also treat Searles Lake brine with CO_2 gas to produce additional soda ash and borax.

Death Valley. There appears to be ample evidence that, during a part of Quaternary time, Death Valley received the overflow from the Owens-Searles-Panamint drainage system. Boron-bearing salts, mainly of local derivation, were added to the waters of this lake, and this ultimately resulted in deposition of ulexite ("cotton ball"—$NaCaB_5O_9 \cdot 8H_2O$) in the playas on the floor of Death Valley. From this material borax was once made commercially by leaching with hot water, decanting from the mud, and crystallizing the borax from

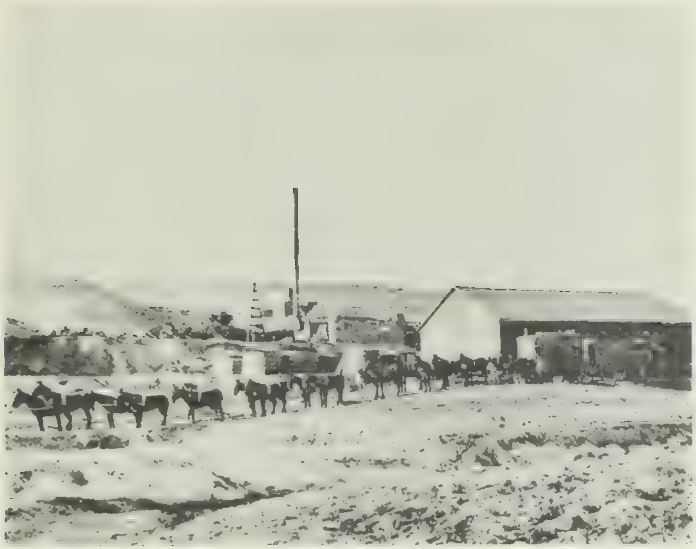

FIGURE 3. Harmony borax works, 1882-1890. *Photo courtesy Pacific Coast Borax Company.*

the liquor. The old Harmony borax works, on the valley floor north of Furnace Creek, is shown in figure 3.

At about the time when production began from the muds of Death Valley and the Amargosa Valley to the southeast, colemanite ($Ca_2B_6O_{11}\cdot 5H_2O$) was discovered in the Funeral Mountains immediately east of the floor of Death Valley. A short time later, commercial deposits of this mineral were found and produced in the Calico Mountains, about 12 miles north of Daggett in San Bernardino County. For several years, colemanite was the major source of borate products, and the extraction of borax from playa deposits was discontinued. In 1890, colemanite in commercial quantities was developed in the mountains that form the east wall of Death Valley, first at the Lila C mine and later in the vicinity of Ryan (fig. 4). Production of colemanite continued from the Funeral Mountain area until 1928, when the Pacific Coast Borax Company completed the transfer of its operations to the Kramer borate district.

The borates of Death Valley region can be divided into two general classes. The younger, or Quaternary, deposits consist mainly of ulexite found in surface layers along the borders of the Death Valley sink. The older, and more important, deposits consist of colemanite, ulexite, and other borate minerals. These occur in bedded sedimentary rocks of Tertiary age (fig. 4).

Cutting back into the Black Mountains in a southeasterly direction from the floor of Death Valley is Furnace Creek Wash, on both sides of which are large deposits of colemanite. The thickest continuous section of Tertiary formations in the region flanks the wash, and is a familiar sight to all travelers entering Death Valley from the east. The borate deposits occur mostly as irregular, roughly bedded masses of crystalline colemanite and ulexite within the playa clays of the Furnace Creek formation. This yellow-weathering clay and interlayered flows of basaltic lava form the bizarre bad-land topography of the lower Furnace Creek area, and many exposures of borate minerals appear along the intricate channels cut by drainage through this area.

Farther up Furnace Creek Wash is a considerable group of colemanite and other borate deposits that also are of Tertiary age and are similar to those noted above. The commercial output from some of these has been large, especially from the mines known as the Biddy McCarthy, Grand View, Oakley, and Widow, all in the Ryan area (fig. 1). Another important producer of colemanite was the Lila C mine, which is about 6 miles southeast of the deposits in the Furnace Creek area proper. The output from these colemanite mines was hauled by a narrow-gauge railroad to Death Valley Junction, on the Tonopah and Tidewater Railroad.

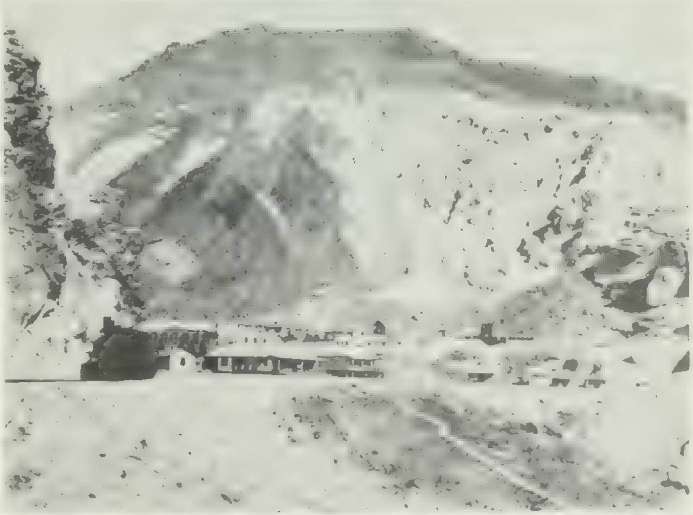

FIGURE 4. Bedded deposits of Tertiary age at Ryan, Death Valley area. *Photo courtesy Pacific Coast Borax Company.*

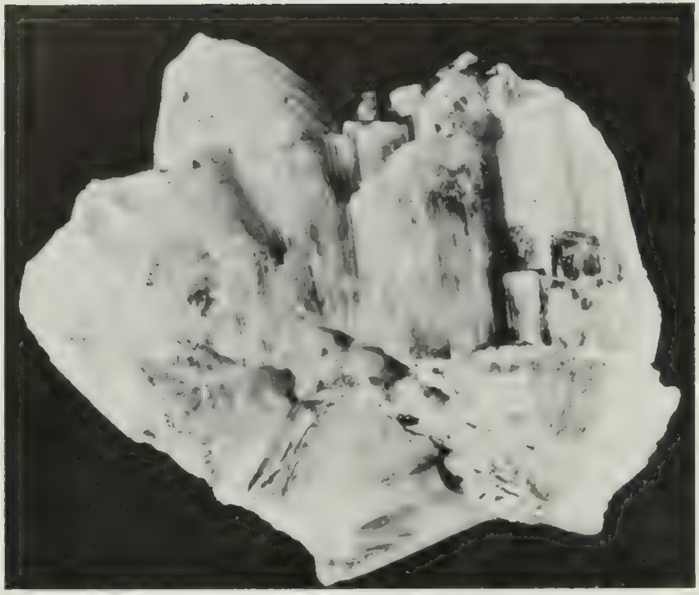

FIGURE 5. Kernite (rasorite), two-fifths actual size. *Photo courtesy Pacific Coast Borax Company.*

Deposits of colemanite later were developed at Shoshone near Death Valley, and at several localities in Ventura and Los Angeles Counties. Of all these, only the Shoshone deposits still produce colemanite.

Kramer Borate District. The Kramer district is about 35 miles from Mojave, California, midway between that town and Barstow. It lies immediately north of Boron, a station on the Santa Fe Railroad. This field is unique in that surface geology did not indicate the presence of the borate deposit, which was discovered in 1913 during the drilling of a water well. Colemanite was recognized in the drill cuttings, and prompted the drilling of more than 40 exploratory wells during the following decade. However, no great progress was made in this field until 1925, when a deposit of tincal ($Na_2B_4O_7 \cdot 10H_2O$) was discovered by drilling. A shaft was then sunk to the deposit, and penetrated large quantities of a new borate mineral, which was named kernite, or rasorite ($Na_2B_4O_7 \cdot 4H_2O$). By 1928, the Pacific Coast Borax Company had transferred its mining operations from Death Valley to this area.

The sodium borate occupies only a portion of the mineralized area, which lies within an irregular oval about 4 miles long and 1 mile in width. The area apparently was a part of a basin of deposition during the period of accumulation of the borates, and the beds form a synclinal structure that is depressed to depths of 1,000 feet or more along its axis. The principal borate deposits range in depth from about 300 to 1,000 feet below the surface of the ground, and are covered by alluvium and other unconsolidated deposits that extend to maximum depths of about 300 feet. Tertiary beds encountered beneath the alluvium consist of an alternation of sediments deposited by flowing or standing waters, and these in turn are underlain by flows of olivine basalt. The borate deposits are included in the sedimentary part of the section, above the lavas, and presumably are of upper Miocene age. They occur in a distinctive series of sedimentary beds designated as the Kramer lake beds. These are described locally by terms such as green shale, blue shale (which includes the borates), and dark gray shale. The blue shale is a fine-grained sediment of colloidal type, and evidently was laid down in standing water.

Colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$) and ulexite ($NaCaB_5O_9 \cdot 8H_2O$) are the most widely distributed of the borate minerals. They are scattered irregularly in the form of nodules or lumps imbedded in the clay or shale that surrounds the sodium borates. It is probable that the ulexite of the Kramer District was formed during late Tertiary time in, or on the borders of, playa lakes, and that in places this mineral was converted to colemanite after burial of the original deposits.

The deposits of tincal and kernite that are now being mined are lenticular in form, and contain impurities of clay and other insoluble materials. The massive sodium borate is not appreciably contaminated by any other soluble constituent.

Most geologists agree that boron or borate salts have been brought to the earth's surface as constituents of volcanic gases or waters. At Kramer it seems evident that the borate-depositing waters issued with, and subsequent to, the outpouring of basaltic lavas over slopes adjacent to the basin in which the lake deposits were later laid down. Volcanic waters probably flowed down through and over the lava masses while these rocks were still hot. Evaporation probably converted the waters to brines, which may have accumulated in pools or lakes in a supersaturated condition with respect to borax. Evaporation and cooling of the solutions probably threw down the borax as tincal.

Kernite, which was first discovered in the Kramer area, seems to have been formed from the original bedded accumulations of tincal by alteration and recrystallization after the deposits had been buried and later firmly consolidated. The conversion from tincal to kernite probably was very slow, and strikingly large crystals of kernite are

FIGURE 6. Twenty-mule team drive, Death Valley. *Photo By Mary R. Hill.*

found. Most of the kernite is intimately associated with tincal, some large masses of which appear to be secondary to the kernite.

Other Deposits of Salines. Substantial deposits of salines also occur in Dale, Danby, Cadiz, Koehn, Soda, Deep Springs, and Mono Lakes. The Salton Sea also contains large amounts of salt, and additional deposits are present as parts of the Tertiary sedimentary section in the Avawatz Mountains. Some of these deposits have been worked commercially, and all can be considered potential sources of saline material.

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3. THE MOUNTAIN PASS RARE-EARTH DEPOSITS [1]

By J. C. Olson [2] and L. C. Pray [3]

Introduction. Rare-earth minerals were discovered near Mountain Pass in northeastern San Bernardino County, Calif., in April 1949, and in the following year the Sulphide Queen carbonate body was found. This body is the world's greatest known concentration of rare-earth metals with a tonnage larger than the total of all rare earths used in the world prior to 1950. The rare earths in the Mountain Pass district are chiefly cerium, lanthanum, and neodymium. These elements occur principally in bastnaesite, a rare-earth fluocarbonate, heretofore reported from only about 10 localities in the world.

The bastnaesite was discovered in samples from Mountain Pass obtained by H. E. Woodward and Clarence Watkins of Goodsprings, Nev., and its identity was established in laboratory studies by E. T. Schenk of the U. S. Bureau of Mines and D. F. Hewett of the U. S. Geological Survey. Subsequent prospecting by individuals and geologic investigations by the U. S. Geological Survey resulted in the discovery of bastnaesite in the Sulphide Queen carbonate body and numerous other deposits in a belt 6 miles long.

Investigations by the U. S. Geological Survey since 1949 (Olson et al., in preparation) include detailed mapping of the site of the initial discovery—the Birthday claims—by L. C. Pray and W. N. Sharp; geologic mapping of the district by J. C. Olson; detailed mapping of the Sulphide Queen carbonate body and several smaller deposits by D. R. Shawe and W. N. Sharp; and laboratory mineralogic investigations by H. W. Jaffe.

General Geology. The area of known rare-earth mineral occurrences in the Mountain Pass district lies within a belt of pre-Cambrian metamorphic and igneous rocks that is bounded on the east and south by the alluvium of Ivanpah Valley. The west boundary is the Clark Mountain fault, a west-dipping normal fault along which the Paleozoic sedimentary rocks and Mesozoic sedimentary and volcanic rocks on the hanging wall have been displaced as much as 12,000 feet relative to the pre-Cambrian rocks of the footwall (Hewett, in preparation). The north boundary is formed by a conspicuous transverse fault that cuts the Clark Mountain fault and is just a few hundred feet north of the Birthday shaft. Although pre-Cambrian rocks crop out north of this fault for 10 miles, they are not known to contain any rare-earth mineral deposits or alkalic igneous rocks.

The pre-Cambrian metamorphic complex consists of hornblende and mica gneisses and schists, locally containing sillimanite or coarse garnet; biotite granite gneiss with coarse rectangular or eye-shaped feldspar grains; light-colored granitic augen gneiss and associated pegmatites; and minor dike rocks of mafic to intermediate composition. All these pre-Cambrian metamorphic rocks have a foliation that strikes generally north to northwest—about parallel to the general trend of the Clark Mountain fault—and dips are 50-80° W. in most places. Units based upon the relative proportions of the various pre-Cambrian rock types have been recognized but are not delineated on the accompanying map (pl. 1).

Igneous Rocks. The metamorphic complex is intruded by igneous rocks of two groups. The older group consists of potash-rich rocks which range in composition from shonkinite through syenite to granite. These rocks are related to the carbonate and rare-earth mineralization and are considered pre-Cambrian. The second group, which includes dikes of andesite, basalt, and rhyolite, is distinctly younger and is probably of Tertiary age. Most of the potash-rich dikes trend northwest, parallel to the regional foliation of the metamorphic complex, whereas the younger andesitic dikes trend generally east.

The potash-rich intrusive rocks occur in several hundred thin dikes and in seven larger intrusive bodies. Most dikes appear to dip southwest at moderate to steep angles, but exceptions are numerous among the thinner dikes. The largest intrusive body, near the Sulphide Queen mine, is composed largely of shonkinite and mafic syenite and is about 6,000 feet long and 1,800 feet wide. Of the other six intrusive bodies, the two nearest U. S. Highway 91 are leucosyenites, with 2 or 3 percent quartz; the southeasternmost is chiefly red granite; and the other three are composite shonkinite-syenite bodies.

The shonkinite is the oldest of the potash-rich rocks, and the syenite, quartz syenite, and granite are successively younger. However, the youngest of the potash-rich rocks are dikes of fine-grained shonkinite. Thin dikes of all the potash-rich rocks occur throughout the district and in general are finer grained than the same rocks in the seven larger intrusive bodies.

The shonkinite is typically a coarse-grained rock composed of about equal amounts of distinctive grayish-red microcline, green

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[1] Publication authorized by the Director, U. S. Geological Survey. Contribution No. 660, Division of the Geological Sciences, California Institute of Technology.

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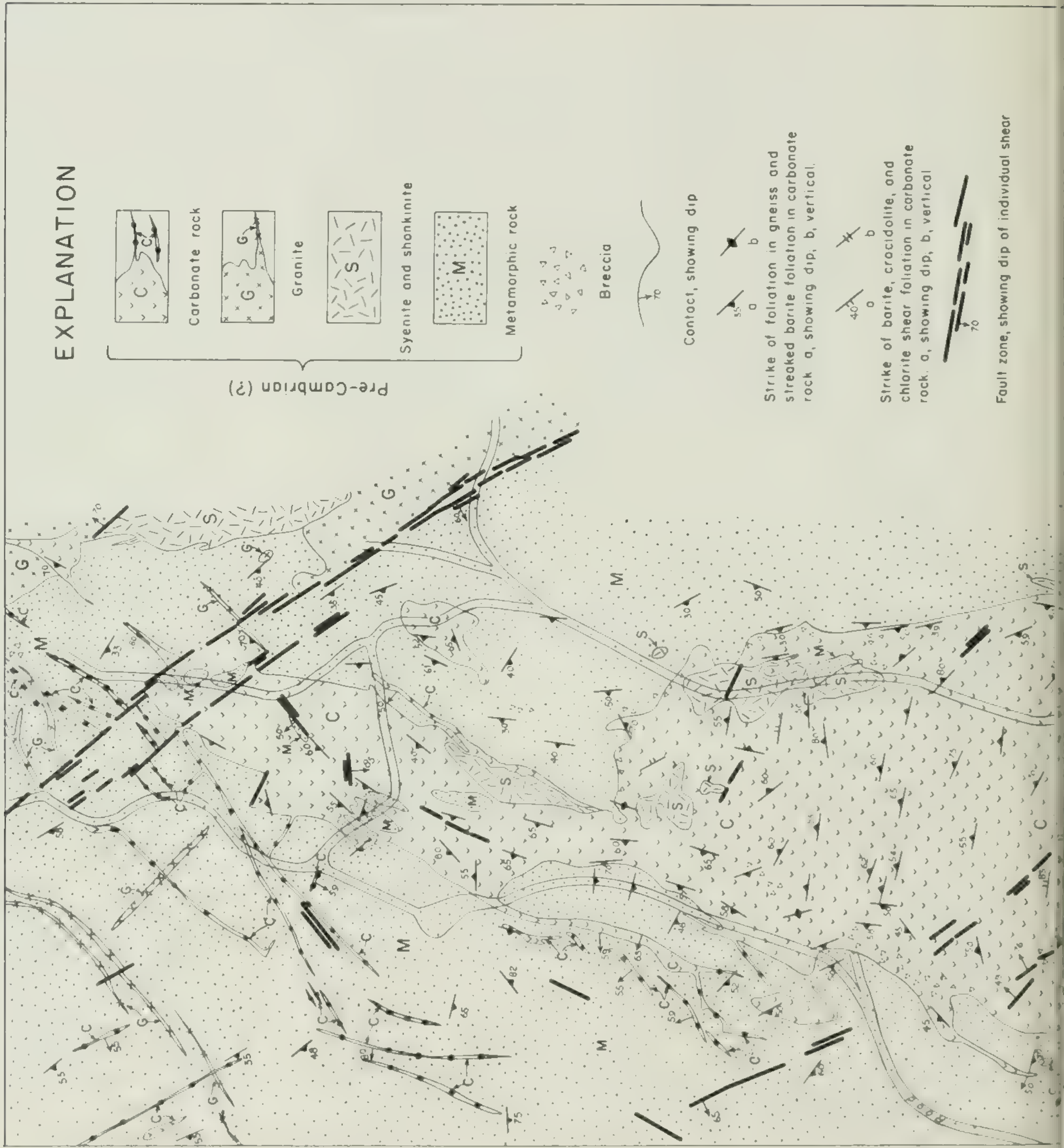
EXPLANATION
C
C'
Carbonate rock
G
Granite
S
Syenite and shonkinite
M
Metamorphic rock
Pre-Cambrian (?)
Breccia
70
Contact, showing dip
55
a
b
Strike of foliation in gneiss and streaked barite foliation in carbonate rock a, showing dip, b, vertical.
40
a
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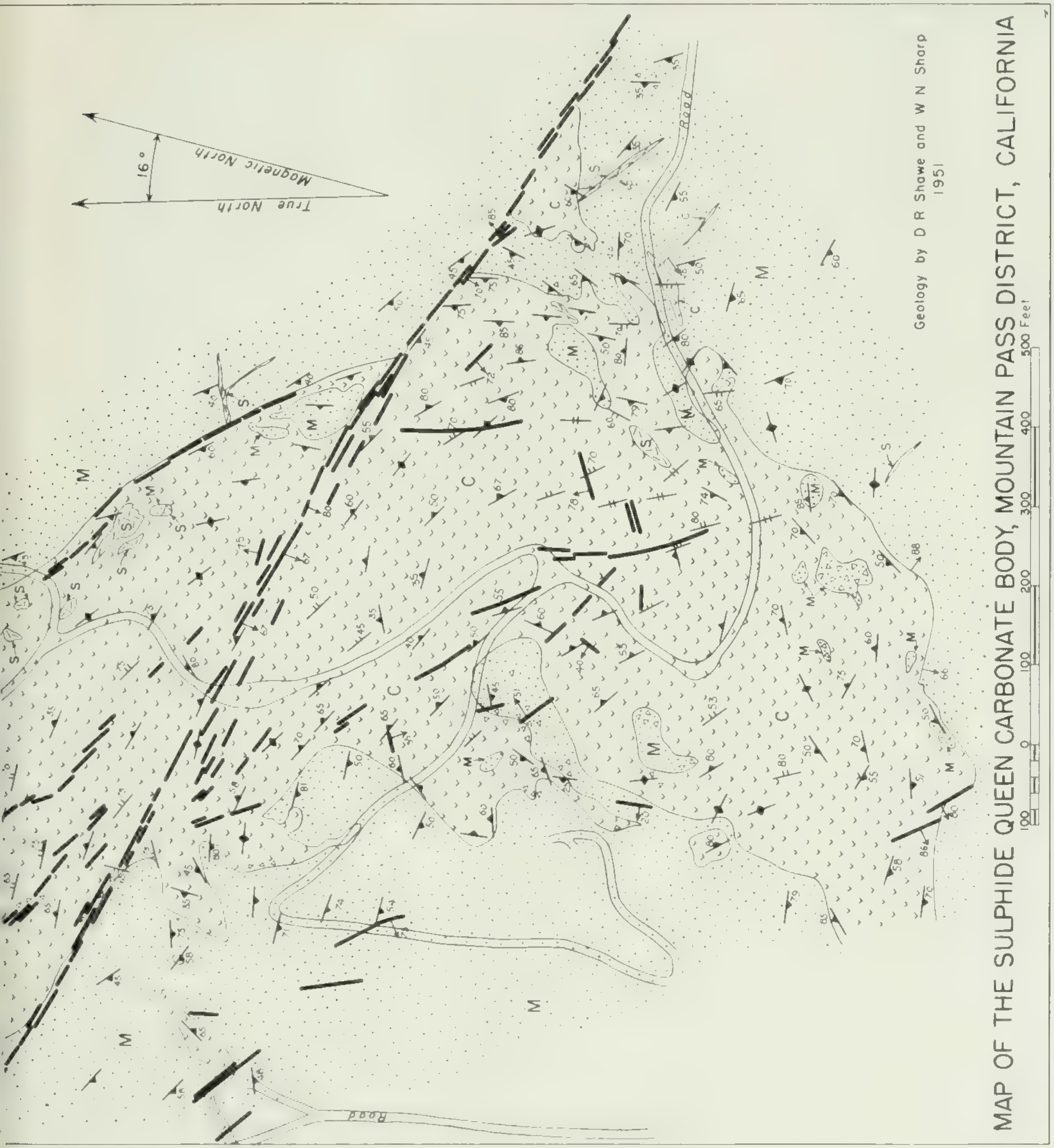
Strike of barite, crocidolite, and chlorite shear foliation in carbonate rock. a, showing dip, b, vertical
70
Fault zone, showing dip of individual shear


MAP OF THE SULPHIDE QUEEN CARBONATE BODY, MOUNTAIN PASS DISTRICT, CALIFORNIA

Geology by D R Shawe and W N Sharp
1951

FIGURE 1.

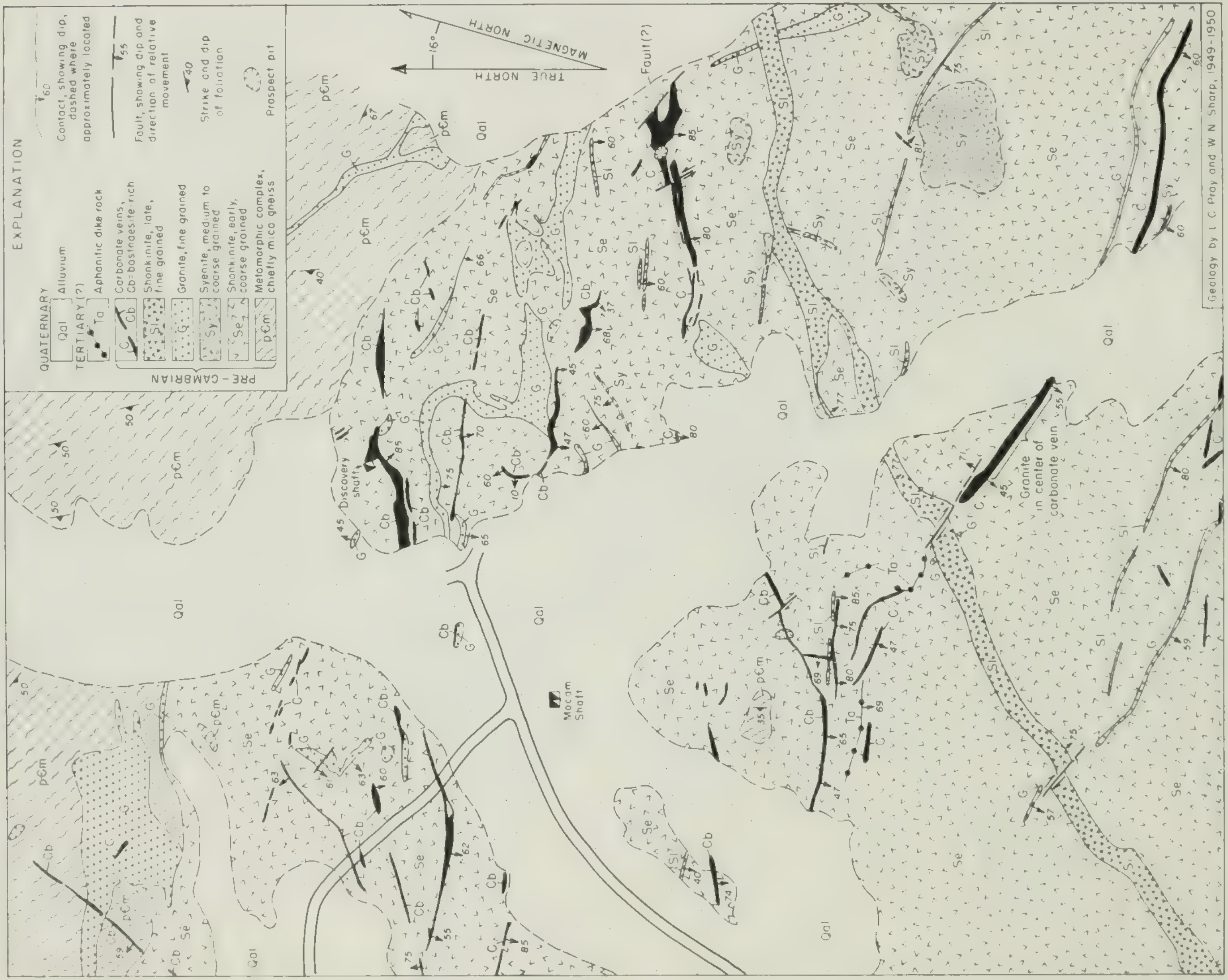

EXPLANATION
QUATERNARY
Qal
Alluvium
TERTIARY(?)
Ta
Aphanitic dike rock
PRE-CAMBRIAN
C Cb
Carbonate veins, Cb=bastnaesite-rich
Sl
Shonkinite, late, fine grained
G
Granite, fine grained
Sy
Syenite, medium to coarse grained
Se
Shonkinite, early, coarse grained
p€m
Metamorphic complex, chiefly mica gneiss
Contact, showing dip, dashed where approximately located
Fault, showing dip and direction of relative movement
Strike and dip of foliation
Prospect pit
TRUE NORTH
MAGNETIC NORTH
16°
Fault(?)
Discovery shaft
Mocam Shaft
Granite in center of carbonate vein
SCALE
0
50
100
200
300 FEET
Geology by L C Pray and W N Sharp, 1949-1950

FIGURE 2. Map of the eastern part of the Birthday claim area, Mountain Pass district.

augite, and biotite. With decrease of pyroxene and biotite and increase in potash feldspar, the shonkinite grades into syenite, and this in turn grades into granite with 10 to 40 percent quartz and less than 10 percent mafic minerals. Amphiboles are common constituents of the potash-rich rocks, and sodic varieties such as riebeckite, arfvedsonite, and sodic hornblende are widespread. Aegirine and aegirine-augite occur in feldspar-rich pockets within the shonkinite. The fine-grained shonkinitic dikes differ mineralogically from the older coarse-grained shonkinite: they contain several percent quartz, more sodic amphibole or aegirine-augite, and less augite. All the potash-rich rocks are interpreted as products of a single period of intrusive activity, a period during which the temperatures of the invaded rock appear to have progressively decreased, as shown by fine-grained "chilled" borders on some of the youngest potash-rich rocks.

The genetic affinity among the various potash-rich rocks is indicated by field and petrologic relationships and by chemical and spectrographic analyses. Analyses of two shonkinites, one coarse syenite, one fine-grained granite, and one shonkinitic dike rock show a range in K_2O content from 7.0 to 11.2 percent, compared to a range in Na_2O content of 0.26 to 1.4 percent. Analyses of these same samples also show an abnormally high content of barium and strontium oxides (0.26 to 1.2 percent) and of the cerium group of rare earths (0.03 to 0.4 percent La), indicating the genetic relationship of potash-rich rocks to the carbonate rocks.

The carbonate rocks cut and are therefore younger than the potash-rich igneous rocks, although one possible exception was noted on the Birthday claims where a thin vein appeared to be cut by a shonkinitic dike a few inches thick. Radioactive age determinations on monazite from the Sulphide Queen carbonate body of about 900 to 1,000 million years (Jaffe, H. W., in preparation) suggest a probable Proterozoic age for the rock. The potash-rich igneous rocks are older than the carbonate rock, though closely related, and thus are pre-Cambrian.

Many dikes of aphanitic to fine-grained rock, chiefly andesitic but ranging in composition from basalt to rhyolite, cut all the other rocks and on the basis of regional evidence are considered Tertiary(?) in age. These dikes are 1 foot to 20 feet thick, are vertical or dip steeply, and occur mostly in four swarms of east-trending dikes.

Carbonate Rocks. About 200 veins composed largely of carbonate minerals but commonly containing abundant barite and quartz have been mapped in the district. Most of these veins are 1 foot to 6 feet thick. They cut across the pre-Cambrian foliation and all the dike rocks. Some appear to have been emplaced in fractures in the shonkinite-syenite intrusives. One remarkable deposit, called the Sulphide Queen carbonate body because of its proximity of the old Sulphide Queen gold mine, is estimated to have at least 10 times the surface area of all the other carbonate veins exposed in the district. The Sulphide Queen carbonate body is 700 feet in maximum width, 2,400 feet long, and appears to dip to the west at a moderate angle. It is similar mineralogically to many of the veins in the district.

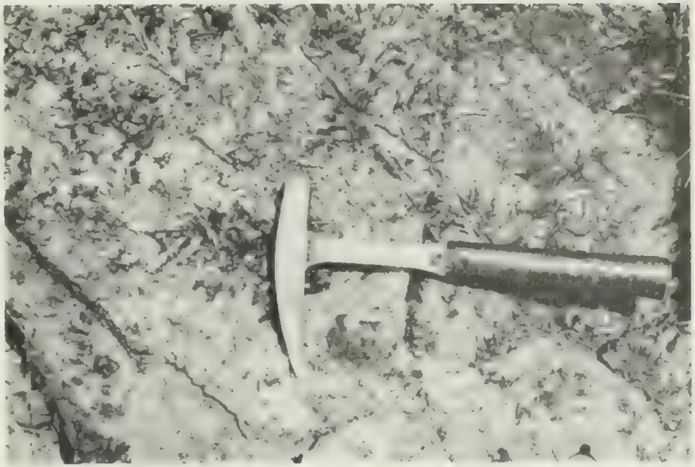


FIGURE 3. Outcrop of bastnaesite-rich vein on Birthday claims. Tabular bastnaesite crystals and whitish patches of barite weather out in relief above dominant calcite matrix.

The distribution of carbonate rocks and veins in the district is shown on the geologic map (pl. 1). The known rare-earth and thorium deposits are most abundant in a belt, in places 3,000 to 4,000 feet wide, that trends northwest for about 5 miles from the southeast corner of the map area to the vicinity of the Birthday shaft. This belt is offset by several transverse faults and appears to be terminated by the transverse fault north of the Birthday shaft.

Although no large fault has been mapped in or parallel to the rare-earth and thorium belt, many small northwest-trending faults are exposed for short distances, and these contain local deposits of rare earths and thorium. The abundance and size of the carbonate bodies in the belt appear to be spatially related to the potash-rich intrusive rocks, for the greatest concentration is in and along the southwest side of the largest shonkinite-syenite body. Mineralized shear zones in this belt cut the shonkinite-syenite body and related dikes, as well as the carbonate veins, yet they locally contain rare earths, thorium, barite, and other constituents of the veins. Hence faulting occurred after the main period of deposition of the carbonate rocks, but there was some circulation of mineralizing solutions after the faulting.

The dominant carbonate minerals, which constitute at least half of most veins, are calcite, dolomite, ankerite, and less commonly siderite. Barite is a widespread vein mineral, averaging 20 or 25 percent of the carbonate rock in the district and locally exceeding 65 percent. The barite contains variable amounts of strontium, and some barian celestite is present.

The rare-earth minerals thus far recognized include bastnaesite, parisite, monazite, allanite, sahamalite (Jaffe et al., 1953), and cerite. Of these the most abundant is bastnaesite, which constitutes 5 to 15 percent of much of the Sulphide Queen carbonate body and locally exceeds 60 percent.

Quartz occurs in the veins in various proportions, generally from 5 to 40 percent but ranging from nearly 0 to 100 percent. Other minerals found in the carbonate rocks include crocidolite, chlorite, biotite, phlogopite, muscovite, sphene, magnetite, hematite, goethite, galena, pyrite, chalcopyrite, tetrahedrite, malachite, azurite, cerussite, strontianite, aragonite, wulfenite, fluorite, apatite, and thorite.

Structural features of the Sulphide Queen deposit are shown in figure 1. Breccia fragments of older rocks such as gneiss, syenite, and carbonate rock are present locally in the Sulphide Queen carbonate body, chiefly near the walls, as well as in several other breccia veins. Some of the angular feldspathic wall-rock fragments in the Sulphide Queen carbonate body are but little rotated, but in other places aggregates of well-rounded fragments of several rock types indicate movement from their original positions in the country rock. The feldspathic fragments are typically coated with reaction rims of dark phlogopite or biotite.

A planar structure is evident in many of the carbonate deposits. Part of this layering or banding is apparently a primary feature of the veins. Part of the planar structure appears to be a foliation due to shearing and is generally parallel to the walls of the carbonate body. Barite grains, some of which are strung out along streaks in the rock, are commonly eye-shaped as in an augen gneiss, and the elongate grains parallel the walls of the vein. These grains are very common in the Sulphide Queen carbonate body. The foliation and inclusions in this body and its discordance to the foliation of the gneissic wall rocks suggest that the carbonate mass was intruded into its present position.

Origin of the Deposits. The interpretation of the origin of the Mountain Pass rare-earth deposits involves three related features: the group of potash-rich igneous rocks ranging in composition from shonkinite to granite, the carbonate rock that occurs in the notable Sulphide Queen carbonate body and in at least 200 thinner veins, and the exceptionally large concentration of rare-earth metals of the cerium group. These three features are associated spatially, and probably genetically, and are thought to have had their origin during a single geologic episode.

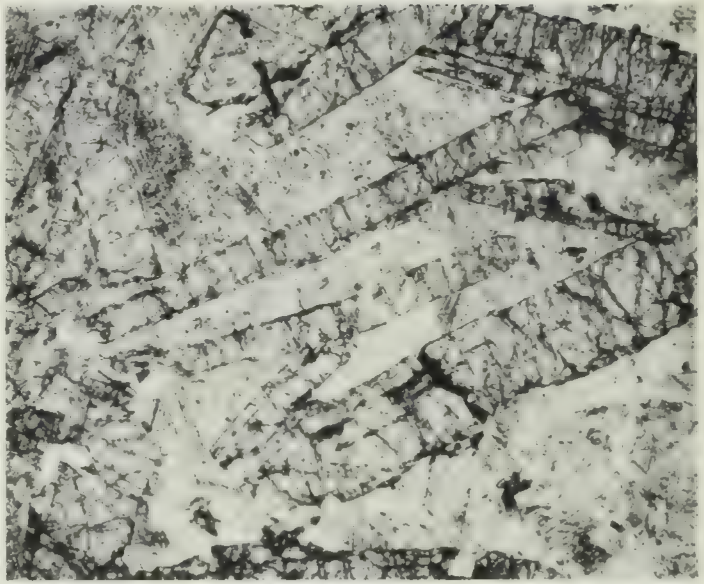


FIGURE 4. Photomicrograph of tabular bastnaesite crystals in calcite matrix. (25x, plane polarized light)

The association of alkalic igneous rocks and carbonate rocks has been reported from many areas of the world. Among those which appear to be somewhat similar to Mountain Pass are Alnö, Sweden; Fen, Norway; several localities in South Africa; Magnet Cove, Ark.; and Iron Hill, Colo. The large amount of carbonate rock in these areas has been interpreted in several ways, principally as either a magmatic product or as inclusions of sedimentary limestone. At Mountain Pass, as in most of the other areas, there is no known sedimentary limestone in the invaded pre-Cambrian rocks. The Sulphide Queen carbonate body is enclosed in pre-Cambrian gneisses rather than in an igneous rock.

Geochemical data from many parts of the world indicate that the cerium group of rare earths tend to be associated with alkalic igneous rocks. The rare-earth elements in part occur in small amounts in the major rock-forming minerals. They also form independent minerals, such as monazite or allanite, disseminated as accessory constituents in various igneous rocks. These elements are also selectively concentrated in residual products of crystallization, owing in part to their relatively large ionic radii, as shown by the common occurrence of rare-earth minerals in pegmatites. Of the known occurrences of bastnaesite, the primary deposits occur in pegmatites, in contact zones, or in veins closely associated with igneous rocks.

The most plausible mode of origin of these features at Mountain Pass is that the materials forming the carbonate rocks were derived largely by differentiation from the same magmatic source that supplied the potash-rich dike rocks. This hypothesis harmonizes with the evidence of the foliation, breccia fragments, and discordance of the Sulphide Queen carbonate body; with the consistent sequence of emplacement and the close association of the potash-rich dike rocks and carbonate veins in the district; and with the remarkable concentrations of certain rare elements.

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4. TUNGSTEN IN SOUTHEASTERN CALIFORNIA *

By Paul C. Bateman † and William P. Irwin †

INTRODUCTION

California is the leading State in tungsten production, having shipped, between 1904 and 1950, about 39,500 short tons of concentrates containing 60 percent WO_3, which is 30.17 percent of the total United States production (Geehan, 1951, Table 4, p. 4). The dollar value of current production exceeds that of such metals as lead, zinc, and copper. Because tungsten is a strategic metal, a domestic supply to fall back on when imports are threatened or curtailed is of national importance.

The tungsten deposits described in this report lie south and east of the Sierra Nevada, in the region that encompasses the southwestern part of the Great Basin, the Mojave Desert, the eastern part of the Transverse Ranges, and the Peninsular Ranges. The western boundary of the region is a line that coincides along a part of its length with the eastern boundary of Los Angeles County. With the notable exceptions of Atolia and Darwin, the deposits in this region have yielded only small amounts of tungsten. Most of the productive deposits in California are in the Sierra Nevada, and the map showing the distribution of tungsten deposits (fig. 1) includes most of those in the Sierra Nevada as well as those in southeastern California.

Little information on the tungsten deposits in southeastern California has been published, but the important tactite deposits in the Sierra Nevada have been described in several papers and reports, which are included in the list of references at the end of this paper. Published reports on tungsten deposits or areas have been used freely as sources of information in the preparation of this paper. Most of the factual data, however, have been obtained from unpublished reports prepared for the files of the U. S. Geological Survey by D. M. Lemmon, D. G. Wyant, M. P. Erickson, E. M. MacKevett, and the writers.

TYPES OF DEPOSITS

Four geologic types of deposits have been recognized in California: tactite deposits, quartz vein deposits, pegmatite deposits, and placer deposits. Quartz veins and placers at Atolia yielded most of the production in the State prior to 1918, but since then the larger part has come from tactite deposits, especially from those in the Sierra Nevada near Bishop. The Pine Creek mine near Bishop accounts for half or more of the current production, and has the largest tungsten reserve in the United States (Bateman, 1945, p. 233).

The only important tungsten-bearing minerals are scheelite ($CaWO_4$) and members of the wolframite group, principally wolframite [$(Fe,Mn)WO_4$] and huebnerite ($MnWO_4$). Ferberite, the iron-rich end member of the wolframite group, is rare in California but important elsewhere. Scheelite is found in all types of deposits, whereas wolframite and huebnerite are present only in quartz veins and pegmatites.

Tactite Deposits. "Tactite," a term coined by Hess (1918) and now in common usage in connection with tungsten mining, has been defined by him as "a rock of more or less complex mineralogy formed by the contact metamorphism of limestone, dolomite or other soluble rocks into which foreign matter from the intruding magma has been introduced by hot solutions." The older European term "skarn" probably is synonymous, and "garnetite" is a partial equivalent. No single mineral is considered essential to tactite. Most tactite masses contain red-brown to yellow-brown garnet of the andradite-grossularite series, commonly in association with either green pyroxene of the diopside-hedenbergite series or with epidote. Quartz and calcite are present in most tactite masses, and are abundant in some. Idocrase, hornblende, clinozoisite, scapolite, feldspar, and fluorite are less common. Metallic sulfides and oxides found in tactite include pyrite, pyrrhotite, molybdenite, bornite, chalcopyrite, sphalerite, bismuthinite, magnetite, and hematite.

Most tactite masses are developed in comparatively pure limestone or marble, but some occur in dolomitic, siliceous, or argillaceous calcareous rock. Commonly tactite borders a contact with granitoid rock; at a few places surface exposures of granitoid rock adjacent to the tactite are lacking, although they generally are present within a few hundred feet. Limestone or marble adjacent to tactite commonly contains light-colored minerals such as wollastonite, diopside, and tremolite in amounts sufficient to permit distinction of the rock from both the main calcareous body and the tactite during the course of mapping. Tactite does not occur along all contacts between marble or limestone and intrusive rock, and is notably irregular in thickness where it does occur.

Scheelite, where present, commonly forms grains that range from pin-point size up to a quarter of an inch across. Crystals an inch

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* Publication authorized by the Director, U. S. Geological Survey. Prepared in cooperation with the California State Division of Mines.

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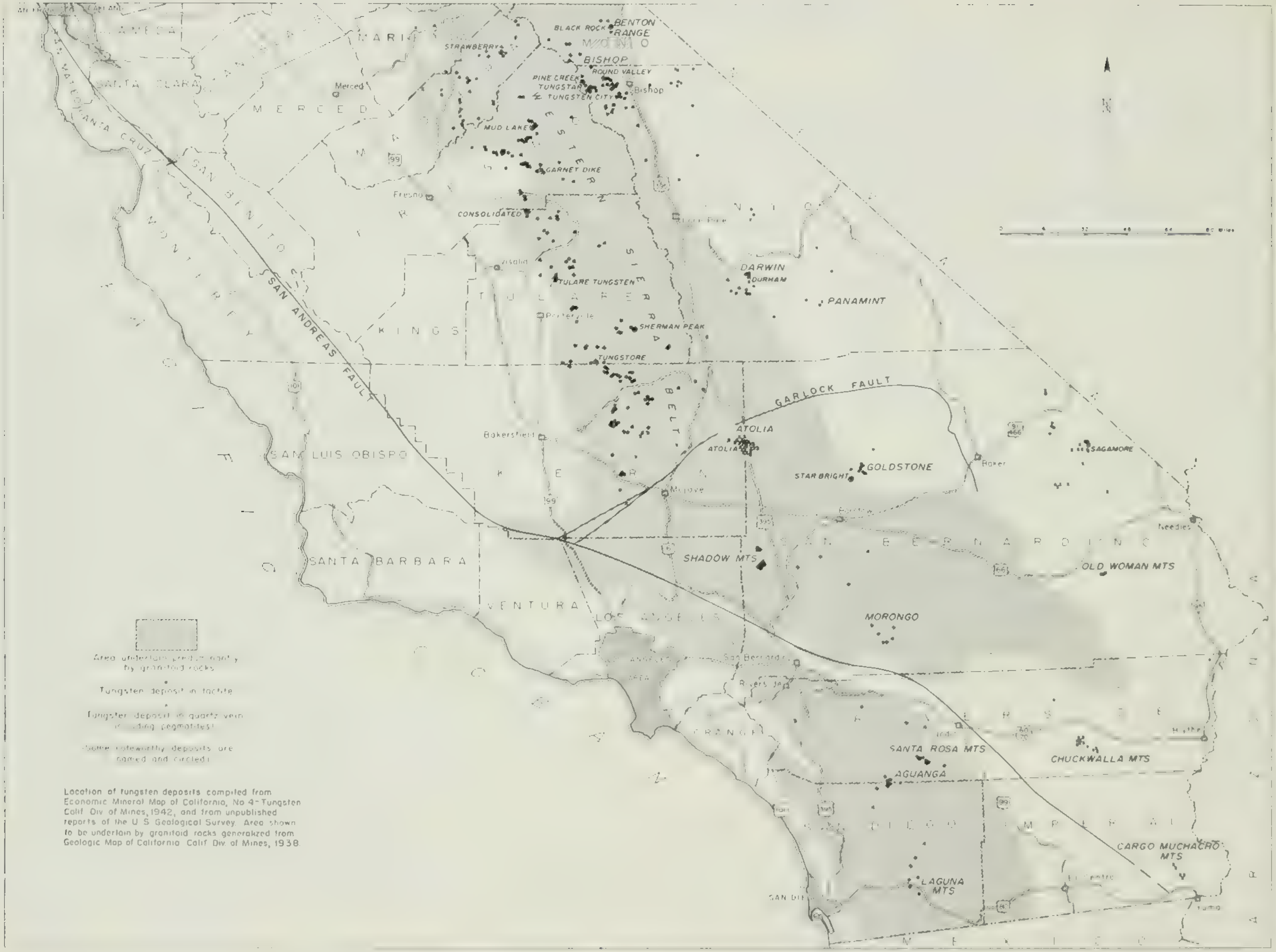


Location of tungsten deposits compiled from Economic Mineral Map of California, No 4–Tungsten Calif Div of Mines, 1942, and from unpublished reports of the U S Geological Survey. Area shown to be underlain by granitoid rocks generalized from Geologic Map of California Calif Div. of Mines, 1938.

FIGURE 1. Map showing distribution of tungsten deposits in the southern half of California.

or more in average diameter are present locally, and in some deposits such coarse crystals predominate. Scheelite typically is distributed erratically through the tactite, and only rarely do all parts of a tactite mass contain sufficient scheelite to constitute ore. During 1953 most tungsten ore contained 0.5 to 1.0 percent of WO_3, but some ores contained 2.0 percent or more. Rock that contained less than 0.5 percent of WO_3 could be exploited profitably during 1953 only if conditions for low-cost mining and milling were exceptionally favorable.

Quartz Vein Deposits. Tungsten deposits in quartz veins, although fewer than those in tactite, have been the source of nearly half of the tungsten produced in California, due primarily to the very productive veins at Atolia. Quartz vein deposits can be conveniently divided into two groups: (1) those in which scheelite is the sole economic mineral, or is associated only with gold, and (2) those in which scheelite or huebnerite is associated with base-metal sulfides. The first group is typified by the veins at Atolia, and the second group by many veins in northeastern San Bernardino County. Calcite is a common minor constituent in the gangue of many veins of the first type, but it has not been observed in any of the base-metal-bearing veins. Tungsten minerals generally are present in base-metal-bearing veins in amounts too small to be mined for tungsten alone, but the tungsten might be recovered profitably as a by-product if the veins were mined for their base metals.

Pegmatite Deposits. Pegmatite bodies containing tungsten minerals are known from several areas of quartz vein deposits, but are common only in the Chuckwalla Mountains. Typically the tungsten is present as pods and stringers of scheelite and huebnerite that are too small to be of economic value.

Placer Deposits. Placer deposits of tungsten are uncommon in California, presumably because scheelite, the principal tungsten mineral in the State, is easily shattered and reduced to slime. All of the known placer deposits are closely associated with their bedrock sources. The largest deposits are at Atolia, where scheelite and gold derived from nearby quartz veins are present in pediment gravels. At the Scheelore mine, high in the Sierra Nevada, scheelite has been recovered from talus below tactite deposits.

DISCOVERY AND MINING HISTORY

Tungsten deposits have been mined actively in California since 1904, when scheelite was first recognized in gold placers south of Atolia. For nearly a decade prior to this time, scheelite had been discarded with the waste from these placers. The first lode mining for tungsten ore was in a scheelite-bearing quartz vein on the Papoose claim south of Atolia, and by 1906 a carload of tungsten ore had been mined and shipped to Germany. Other discoveries followed rapidly.

Scheelite was not recognized in tactite deposits until 1913, when J. G. Powning identified exceptionally large crystals in a tactite outcrop while retrieving a jackrabbit he had shot (Knopf, 1917, p. 231). This discovery in the Tungsten Hills near Bishop became the site of the Jackrabbit mine, and stimulated interest in prospecting other bodies of tactite. Under the impetus of high prices paid for tungsten during World War I, many of the newly discovered deposits were brought into production. At the end of the war the prices collapsed spectacularly, and most of the mines were closed. In 1924, the mines at Atolia were reopened, and others were reopened during the ensuing years.

In the years immediately preceding World War II, the price of tungsten ore once again rose, and concomitantly the ultraviolet light came into general use as a means for prospecting. This combination resulted in a new wave of discoveries and the reopening of many older deposits. During World War II the price and sale of tungsten concentrates were fixed by Federal Law, but with the end of the war, Government contracts to purchase concentrates were cancelled and the price declined, forcing curtailment or abandonment of many operations.

Following the outbreak of hostilities in Korea, the Federal Government in 1951 established a 5-year domestic purchase program, during the course of which tungsten concentrates have been purchased at a price of $63.00 per unit (20 pounds of contained WO_3). With stabilization of the market, production once again has increased.

OUTLOOK

The probability of a continuing vigorous tungsten mining industry appears better now than at any time in the past, owing largely to the stabilizing effect of the domestic purchase program of the Federal Government. This program is favorable to the investment of private capital in long-range mine development. There also is good likelihood that discovery of new deposits will continue, although at a lesser rate than in the past. As compared with most other metals, tungsten has a short commercial history. It was not sought by early prospectors, and it has been used in industry for only about 50 years. Further, the ultraviolet light has been used in prospecting only since 1936, and it is unlikely that all of the exposed quartz veins and tactite deposits have been examined for scheelite. The discovery of new deposits by surface prospecting during the past few years supports the view that new deposits will be found.

DISTRIBUTION AND DESCRIPTION OF DEPOSITS

More than 425 tungsten deposits are known in California, of which 85 percent are tactite deposits and 15 percent are quartz vein deposits. Most of them are in the southern half of the state, where they are commonly found in well-defined districts (fig. 1). In many districts all the deposits are of the same geologic type, but in a few both tactite and quartz vein deposits are present.

Tactite deposits are most abundant in the main area of batholithic rocks of Mesozoic age in California, but they also are associated with isolated batholiths and stocks of uncertain age farther east. The quartz vein deposits, with the notable exception of the veins at Atolia and in the southern Sierra Nevada, lie east of the main area of batholithic rocks in the region where only smaller intrusive masses are found. Pegmatite deposits are found locally in the same areas as the quartz vein deposits, but none have been exploited profitably. Placer deposits are important only at Atolia.

Darwin District. The Darwin district is best known for its production of silver-lead ore, which has been mined intermittently since the 1870's (see Carlisle, et al., Contribution No. 5, this chapter). Scheelite was identified in the Darwin Hills in 1916, but it was not exploited until World War II, when approximately 30,000 units of WO_3 was produced from 45,000 tons of ore. Most of the tungsten production came from lead-poor deposits in the southeastern part of the district, but scheelite also occurs sparingly with the lead ores. The tungsten deposits have been described by Wilson (1943). Both the lead deposits and the tungsten deposits are closely associated with the Darwin quartz diorite stock. The principal tungsten production was obtained from the Durham, Fernando, and Hayward mines (fig. 2). In the past few years the Anaconda Copper Mining Company has stockpiled tungsten ore mined from its lead deposit, but none of this ore has been treated.

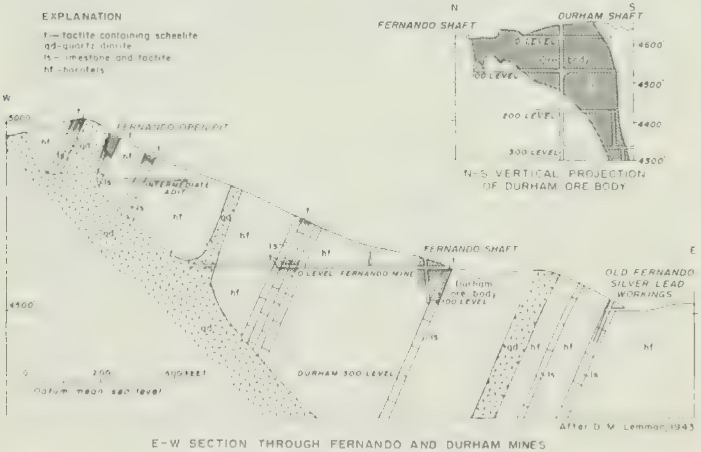


FIGURE 2. Idealized section through Fernando and Durham mines, Darwin district, Inyo County.

The main tungsten ore bodies are in tactite developed in steeply dipping limestone beds adjacent to mineralized cross faults. The limestone is interstratified with dense hornfels of variable mineralogic composition. Deposition of galena and lesser amounts of sphalerite and bismuthinite has followed the tungsten mineralization, but only locally do economic concentrations of sulfide ore overlap tungsten ore bodies. The tactite consists principally of idocrase, calcite, limonite or pyrite, fluorite, and scheelite.

The Durham ore body, the most productive in the district, was mined to a depth of more than 300 feet beneath the surface. The strike length of the outcrop was more than 300 feet but the length of the ore body decreased progressively downward to about 30 feet in the deepest workings. The thickness was irregular, but averaged about 10 feet. Scheelite was distributed unevenly through the ore body, but the richest parts were adjacent to cross fractures. In the upper parts of the mine the ore body was in the footwall side of a 40-foot thick limestone bed, but in depth the ore lay along fractures in a stratigraphic zone several feet above the footwall of the bed, so that the lower few feet of the limestone was barren.

Panamint Range. Scheelite has been found chiefly in quartz veins in three areas of the Panamint Range: Panamint City in Surprise Canyon, Trail Canyon, and southeast of Skidoo. In 1951 high-grade tactite ore was shipped from a deposit reported to be in Trail Canyon, but information about this deposit is not available.

In Surprise Canyon scheelite occurs in the same veins that once yielded more than $2,000,000 in silver. The silver ore consists of white quartz with dark layers that contain argentiferous tetrahedrite and lesser amounts of galena, sphalerite, pyrite, and chalcopyrite. Much of the ore is slightly oxidized and contains malachite, azurite, anglesite, cerussite, smithsonite, bindheimite, and cerargyrite. Most of the tungsten ore consists of these same minerals plus scheelite, but some consists of only quartz and scheelite. The scheelite is in small shoots, which in general contain 0.5 percent WO_3 or less, but thin streaks of high-grade ore are present within some of these shoots.

The quartz veins in Trail Canyon are generally thinner and less continuous than those in Surprise Canyon. Most of the scheelite ore is free of sulfides, but some contains substantial amounts of tetrahedrite and its oxidation products. Tactite also is found in Trail Canyon along certain beds of limestone, but in most places this tactite contains no scheelite.

The most recent discoveries in the Panamint Range have been made southeast of Skidoo, where tungsten was found in 1951. In this area scheelite is distributed sporadically in quartz veins that range from thin stringers to masses more than 20 feet thick. Base-metal sulfides have not been reported from these veins.

Atolia District. The scheelite-bearing quartz veins at Atolia contained the largest bodies of high-grade scheelite ore discovered in the United States and possibly in the world. These important deposits have been described by Lemmon and Dorr (1940), and the following brief description is taken largely from their report.

Although the known reserves in the veins are now small, they still supply significant amounts of ore, mainly through the efforts of lessees. In addition to the vein deposits, extensive placer deposits are present in the district. In times past, thousands of miners worked these placers, particularly the "spud patch," an area of especially rich concentrations that contained scheelite in pieces the size and shape of potatoes. Like the veins, the richer placers are depleted, but placer deposits estimated to contain about one-quarter of a pound of scheelite per cubic yard still remain. Although placers of this grade cannot be exploited profitably at the present time, they constitute a noteworthy reserve. Recently the Surcease Mining Company successfully worked placers containing only about 1 pound of scheelite per cubic yard.

All of the more productive veins occur in a series of roughly parallel, loosely branching faults that cut a body of quartz monzonite. Individual faults generally strike eastward and dip steeply southward, but the general trend of the belt is northeast, parallel to the Garlock fault, which lies 9 miles to the north. Displacements on the faults appear to have been mainly horizontal, with the north side displaced to the west. This left lateral movement is similar to that on the Garlock fault. Many small cross faults displace the veins as much as 25 feet, and some have been slightly mineralized. The main productive belt is about 2 miles long. Both ends of the belt are covered, the west end by alluvium and the east end by beds of Miocene age. Underground exploration of the projected extensions of the zone thus far has failed to reveal any additional ore.

Scheelite is the only ore mineral. The gangue consists of quartz and carbonates (calcite, ankerite, dolomite, and siderite) in proportions that vary in the different mines. Pyrite, stibnite, and cinnabar are present locally as minor constituents and the ores in the west end of the district contain considerable phosphorus, although no phosphate mineral has been identified. One of the veins, the St. Elmo, contained a pocket of gold. Scheelite occurs as veinlets, and forms massive chunks in the larger veins. A single specimen of scheelite weighing a ton or more was taken from the Million Dollar stope of the Union mine and was sent to the National Museum in Washington, D. C. (Hess, 1917, p. 940).

The scheelite is localized in nearly vertical ore shoots that become thinner and leaner at depth. The average length of the shoots is about 100 feet, and the width ranges from a few inches to 17 feet. The grade of ore within the shoots ranges from 1 percent to as much as 70 percent WO_3; the average grade of ore mined in 1940 was about 2 percent.

The quartz monzonite adjacent to all the veins has been hydrothermally altered for distances ranging from a few inches to several feet. The altered rock is impregnated with sericite, pyrite, kaolin, and a little chlorite, and generally is greenish gray in color where it is not weathered. Near the surface, where the rock is weathered, it is brownish in color owing to the oxidation of pyrite, but at the surface it is commonly white because of the leaching of iron oxide and the corresponding prominence of kaolin.

The age of the veins is not established, but they appear to be much younger than the enclosing quartz monzonite. They are cut by diabase dikes of probable late Miocene age, and Hulin (1925, p. 72) considers the mineralization to be associated with late Miocene vulcanism. According to Lemmon and Dorr, the texture of the veins suggests deposition near the surface. This implies a sufficiently long time interval between the period of emplacement of the quartz monzonite and the period of vein mineralization, to permit erosion of most of the rock that originally covered the intrusive mass.

Goldstone District. The Goldstone district is primarily a gold mining area. Most of the tungsten occurrences are in thin, irregular selvages of tactite formed in limestone adjacent to granitic sills, although scheelite also is present in quartz veins that have been mined for gold. A few tons of tactite was mined during 1943 and 1944 from small surface workings in the tactite.

The Starbright mine, southeast of the Goldstone district proper, has yielded the only appreciable production. There tactite inclusions occur in the marginal part of a large plutonic mass that ranges in composition from diorite to quartz diorite (fig. 3). The main tactite mass, 60 feet long and about 15 feet thick, dips 30° SE. Thin-bedded hornfels underlies the tactite and separates it from intrusive quartz diorite. The tactite is composed of garnet, calcite, quartz, clinopyroxene, and scheelite. It was mined in an open cut to a depth of about 40 feet, where the tactite mass exposed at the surface pinched

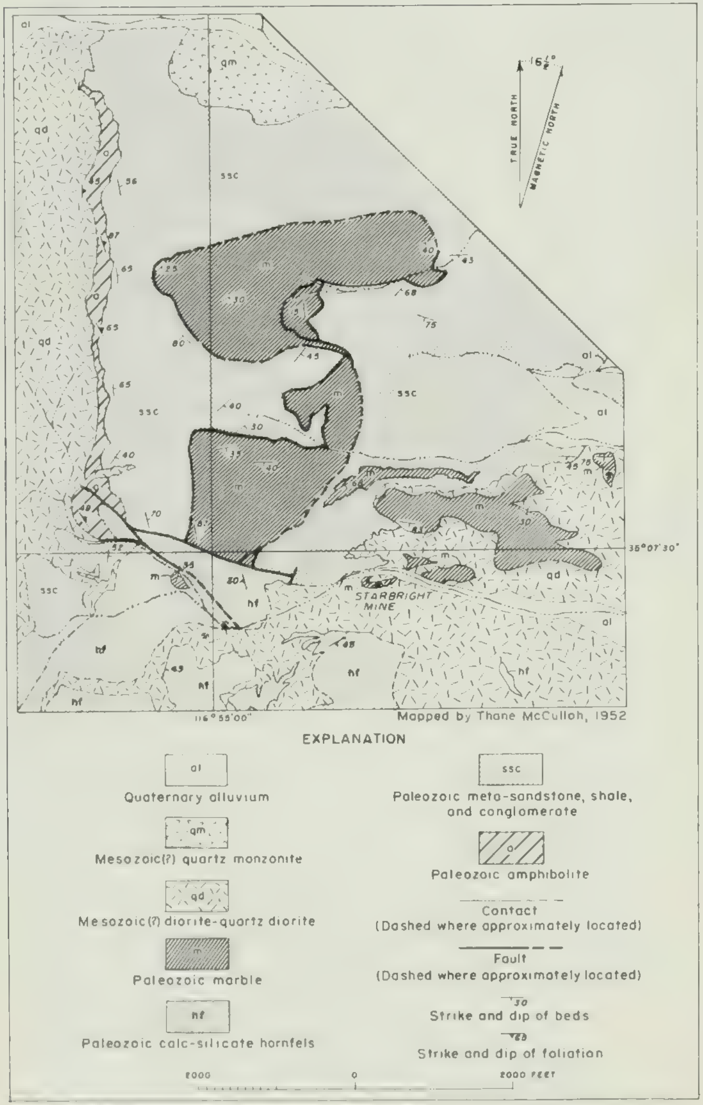

TRUE NORTH
MAGNETIC NORTH
16½°
STARBRIGHT MINE
35°07'30"
116°55'00"
Mapped by Thane McCulloh, 1952
EXPLANATION
al
Quaternary alluvium
qm
Mesozoic(?) quartz monzonite
qd
Mesozoic(?) diorite-quartz diorite
m
Paleozoic marble
hf
Paleozoic calc-silicate hornfels
ssc
Paleozoic meta-sandstone, shale, and conglomerate
Paleozoic amphibolite
Contact (Dashed where approximately located)
Fault (Dashed where approximately located)
Strike and dip of beds
Strike and dip of foliation
2000 0 2000 FEET

FIGURE 3. Starbright mine area, San Bernardino County, California.

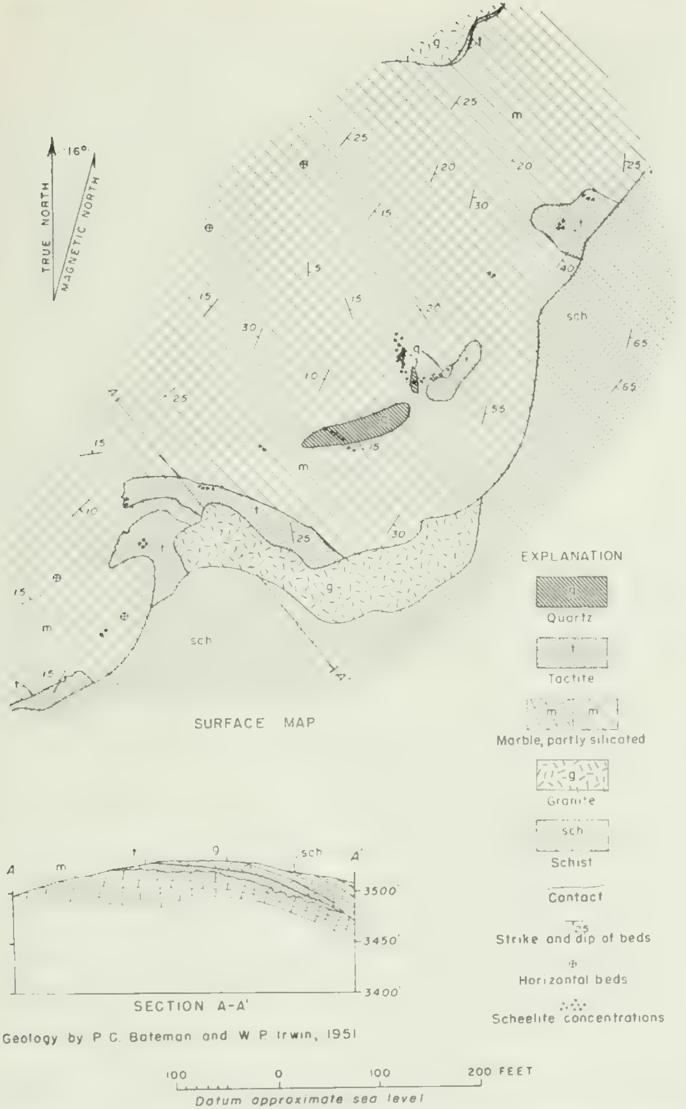
out. Subsequent underground exploration revealed a second scheelite-bearing tactite mass down the projected dip of the surface mass. Two other ore bodies in the same area are similar, but of smaller size.

Deposits in Northeastern San Bernardino County. Scheelite occurs in tactite deposits in the Ivanpah Mountains, and huebnerite occurs with accessory scheelite in quartz veins in the Clark, New York, and Providence Mountains of northeastern San Bernardino County. The production of tungsten is of the order of a few hundred units of WO_3, most of which has come from quartz vein deposits. Most of the quartz veins have been worked mainly for lead, silver, and zinc, and much of the tungsten was recovered as a by-product of base-metal mining. Because the metallurgy of the base-metal ores is difficult, no sustained operation has been carried on. The walls of most veins in granitoid country rock are altered to greisen that commonly contains pyrite and fluorite in addition to abundant muscovite.

The Sagamore mine, on the southeastern slope of the New York Mountains, is in a quartz vein that is typical of those with base-metal sulfides. The vein was discovered in the 1870's and has been worked sporadically since 1890 for lead, zinc, and silver. It is one of several nearly parallel veins that cut across the foliation of enclosing pre-Cambrian (?) schistose quartzite. Although the vein pinches and swells, it can be traced for nearly a mile, and in places it is more than 10 feet thick. Thin, platy crystals of huebnerite are intergrown with galena, sphalerite, chalcopyrite, bornite, and pyrite, and are accompanied by accessory scheelite. Commonly the base-metal sulfides and huebnerite are in layers that parallel the vein walls; less commonly they are intergrown with quartz as vaguely delineated masses in the thicker parts of the vein.

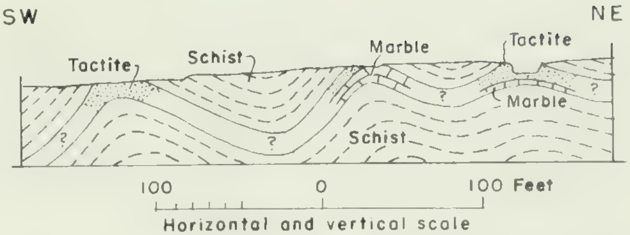
Shadow Mountains. Tactite deposits in the Shadow Mountains, northwest of Victorville, occur in two areas about 6 miles apart. The northern area is called the north field, and the southern area is subdivided in local usage into the middle and south fields. Although scheelite has been known in the district since 1908, the total production is only about 1,000 units of WO_3, owing primarily to the low grade of the ores.

The Just Associates deposit, the most extensive in the north field, is a zone of tactite, silicated marble, and quartz in the upper part of a limestone unit that is overlain by schist (fig. 4). The tactite and silicated marble are developed adjacent to granitic dikes as well as adjacent to a granitic sill that occupies part of the contact between the limestone and schist. Small whitish-fluorescent crystals of scheelite are present in both the tactite and the silicated marble, but are most abundant in streaks in and adjacent to irregular masses of quartz.



Geology by P C Bateman and W P Irwin, 1951

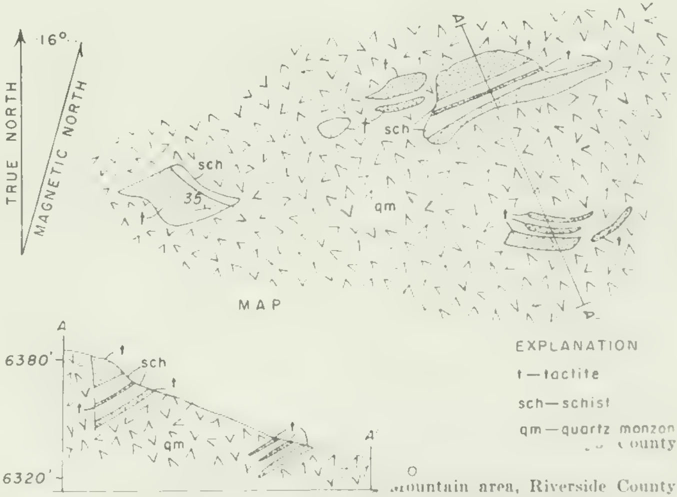
Figure 4. Just Associates deposit, Shadow Mountains, San Bernardino County California.



Geology by M. P. Erickson, 1943

Figure 5. Section through Beacon prospect, Shadow Mountains, San Bernardino County, California.

In the south field the scheelite is distributed in discontinuous ore shoots within tactite masses that locally replace beds of marble that are interstratified with schist and hornfels. Two mineralized beds on the Beacon claims, each about 10 feet thick, have been explored by means of prospect pits and shallow shafts where they appear at the surface in the crests of open anticlinal folds (fig. 5).



County,
Mountain area, Riverside County,
es and Geology, vol. 42, pp. 9-13.

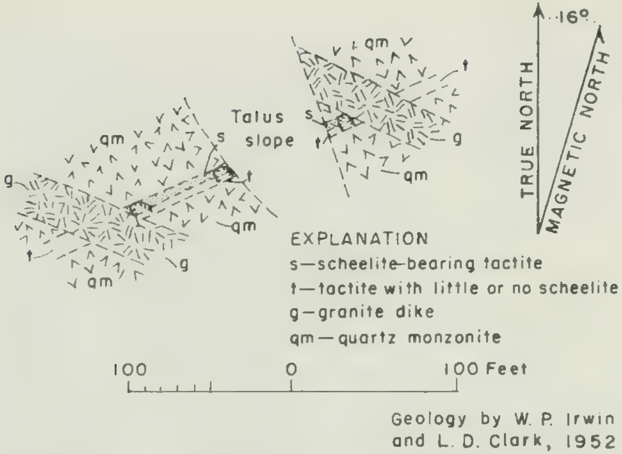

TRUE NORTH
MAGNETIC NORTH
16°
Talus slope
qm
s
t
g
EXPLANATION
s—scheelite-bearing tactite
t—tactite with little or no scheelite
g—granite dike
qm—quartz monzonite
100
0
100 Feet
Geology by W. P. Irwin and L. D. Clark, 1952

FIGURE 7. Sketch of Birthday Star tungsten prospect, Old Woman Mountains, San Bernardino County, California.

Old Woman Mountains. Tungsten in the Old Woman Mountains is found within tactite masses in a northeast-trending belt of metamorphic inclusions in granitic rock. The belt is more than 2 miles long and a quarter of a mile wide. The discovery of tungsten was made by Louis J. Rouchleau in September 1942. Two deposits, the Hidden Value No. 4 (fig. 6) and the Section 9 mines, were ex-
ted during World War II, and yielded more than 1,500 units
recent discovery, the Birthday Star prospect (fig. 7),
1951. The ore at all the deposits is of notably high
ned from the Hidden Value No. 4 and Sec-
to 4.0 percent of WO_3, and the ore in
t probably contains at least 1.0

the prevailing gra-
marble, and
strike

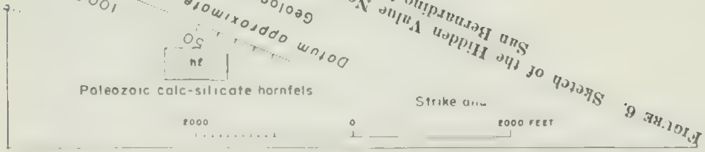


FIGURE 3. Starbright mine area, San Bernardino County, California.

masses that have been explored downward are cut off by granitic rock at shallow depths, and it seems unlikely that any individual mass has very great extent in depth.

Morongo District. Scheelite occurs in the Morongo area, in the eastern part of the San Bernardino Mountains, in both quartz veins and tactite. Production has been small. Tactite deposits are present on the United Tungsten Copper Mines property, the Tungsten Prospecting Associates claims, the Double Cross claim, and at the Sunnyside mine. The tactite is in thin, discontinuous bodies along contacts between marble and granitic rock, and it replaces favorable beds in calcareous strata. At the Sunnyside mine, scheelite also is present as a minor constituent in the Morongo King quartz vein, which has been worked for gold. At the Blue Vase deposit, the scheelite is in thin, gently dipping stringers of quartz.

Chuckwalla Mountains. Tungsten in the Chuckwalla Mountains occurs in quartz veins and pegmatite enclosed in gneiss, schist, and granitic rock. Most of the underground workings were dug for gold, and the added exploration for tungsten has been by means of small, shallow workings. Although some of the pegmatites and quartz veins can be traced for hundreds of feet, the tungsten minerals are largely confined to small shoots or pods, which in some deposits are localized along one wall. Scheelite is the only tungsten-bearing mineral in most of the deposits, but at the Chuckwalla mine, it is accompanied by huebnerite. Although several hundred units of WO_3 have been obtained from the area since the beginning of World War II, production has been intermittent.

Santa Rosa Mountains. Numerous tactite deposits have been found in the northwest end of the Santa Rosa Mountains, in a discontinuous belt of migmatite that trends N. 70° W. The total production from these deposits is small. A few hundred pounds of concentrate was recovered in 1941 in a small mill on the Garnet Queen property, and small shipments for test purposes have been made from the Ragsdale No. 1 and Milky Way No. 4 prospects.

The migmatite is composed of approximately equal amounts of interlayered metamorphic and granitic material. Small discontinuous lenses of tactite, consisting largely of garnet, pyroxene, and
uartz with sparse scheelite, are developed locally in the migmatite.
these lenses have been explored by means of shallow pits
The only underground workings is an old shaft, said
deep (Wright, 1946, p. 13), on the Garnet
ses range in width from 2 to 8 feet
over, the exact length of most
abundan

Laguna Mountains. Scheelite occurs in a number of small, widely scattered deposits in the Laguna Mountains area, where it was first recognized by Eugene Rice in 1940. Tactite is associated with schist in isolated bodies of metamorphic rock in a predominantly granitic terrane. Some of the metamorphic masses are large enough to be considered as roof pendants, some are small inclusions, and in many places the metamorphic and granitic rocks are so intimately mixed that they constitute a migmatite. The Sundown mine, where the most intensive exploration has been carried on, was the site of a small mill in 1943, but the operation did not prove successful.

Cargo Muchacho Mountains. Many of the quartz veins in the Cargo Muchacho Mountains that have been exploited for gold also have been found to contain scheelite, although no production of scheelite has been reported. The gold-bearing veins in which scheelite has been noted are opened by the Cargo Muchacho, Shinebright, Shineright, Gray Point, La Colorado, Padre, and Madre mines. Scheelite, both in quartz veins and in tactite, has been reported from the south end of the Chocolate Mountains, a few miles west of the Cargo Muchacho Mountains, and a few tons of ore has been shipped from these deposits.

The veins in the Cargo Muchacho mine are typical of scheelite-bearing gold veins in the range. They have been developed by means of a 680-foot inclined shaft and by approximately 3,000 feet of level workings from the shaft. The veins are in a series of shear zones, most of which are parallel to the foliation of dark-gray quartz diorite. In the veins, scheelite is localized in tabular zones as much as 100 feet in average diameter and 10 feet thick. The scheelite commonly occurs in the quartz as veinlets and surface coatings, and less commonly it is finely disseminated within the quartz. The scheelite-bearing zones contain little or no gold; conversely, the parts of the veins that are richest in gold contain almost no scheelite.

Aguanga Area. In the area east of Aguanga, in southern Riverside and northern San Diego Counties, scheelite-bearing tactite occurs as lenses in a terrane composed dominantly of schist, gneiss, and granitic rock. The total output from the area is in excess of 3,000 units of WO_3, and the most productive deposits are the Pawnee and Little Goffee (Easy Group) mines. Most of the other deposits are poorly exposed, and have been explored only by means of near-surface workings.

The tactite mass at the Pawnee mine is a tabular body 55 feet long and 8 feet wide at the outcrop, and continues downward with unchanged plan dimensions to the level of the deepest workings, or for a distance of at least 130 feet. The Little Goffee deposit is a tabular mass of tactite with a steep southwesterly dip. It is enclosed by gneiss and granitic rock. In outcrop the tactite mass is 45 feet long and 3 to 5 feet wide. It has been mined in a glory hole to a depth of about 25 feet. An adit that passes a few feet beneath the bottom of the glory hole intersects only calcite marble at the downward projection of the tactite mass.

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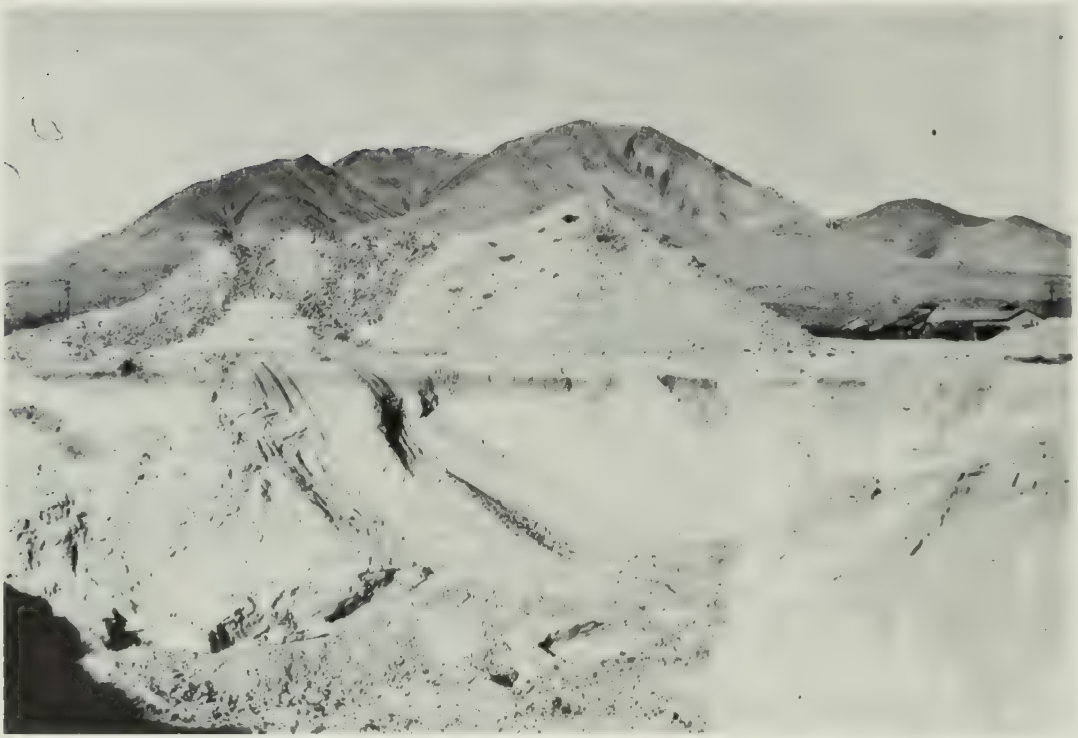

FIGURE 8. Open-cut at Atolia placers, San Bernardino County. *Photo by Mary R. Hill.*

5. BASE METAL AND IRON DEPOSITS OF SOUTHERN CALIFORNIA

By Donald Carlisle,* Dudley L. Davis,** Malcolm B. Kildale,†
and Richard M. Stewart ‡

GENERAL STATEMENT

In addition to tungsten, gold, and silver, the bulk of the metal production from southern California is derived from deposits of lead, silver, zinc, and iron. An appreciable amount of copper is recovered as a by-product from lead-zinc, gold-silver, and tungsten deposits, and minor amounts are taken from a few small copper mines in the central Mojave Desert region, mainly in San Bernardino County. Molybdenum also is recovered as a by-product from some tungsten operations. Manganese has been produced, particularly in war time, from several small deposits in the central and Southern Mojave Desert (San Bernardino, Riverside, Imperial Counties) and in the Coast Ranges (San Luis Obispo County). The mercury deposits at Coso Hot Springs, in Inyo County, yielded about 231 flasks in the period 1931-1940, and several deposits in San Luis Obispo and Santa Barbara Counties represent the southeastern part of the Coast Range mercury belt. A few hundred tons of antimony ore has come from about half a dozen scattered deposits.

Cassiterite is known to occur (1) in quartz-tourmaline veins in granodiorite of the southern California batholith (the Temescal or Cajalco district, western Riverside County), (2) with minor scheelite and sulfides in partly silicated limestone near a contact with granite in the Ivanpah Mountains (Evening Star mine near Cima, San Bernardino County), and (3) with minor scheelite and sulfides in tactite along a contact with granite in the Tehachapi Mountains (Gorman district, Kern County). Some tin has been produced from each of these areas. An interesting occurrence of nickel, with pyrrhotite, pentlandite, and violarite in gabbro of the Julian-Cuyamaca area (San Diego County), has been explored without commercial success. Chromite deposits belonging to the Coast Range belt are mined in San Luis Obispo County. These occur in ultramafic bodies that intrude Franciscan rocks. Large undeveloped reserves of titaniferous magnetite are present in the gabbro-anorthosite complex of the San Gabriel Mountains (see Higgs, Contribution No. 8, Chapter VII).

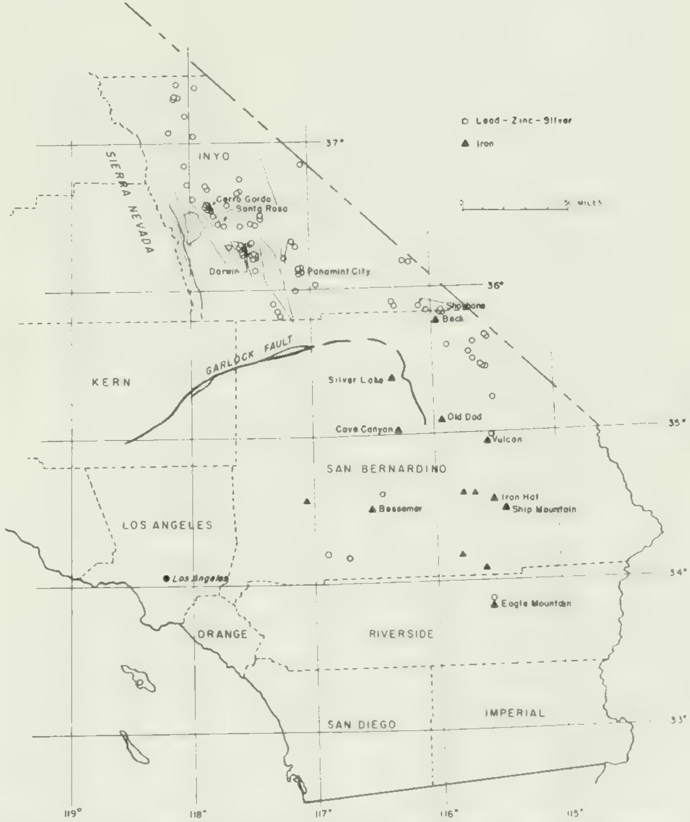

FIGURE 1. Distribution of principal known lead-zinc-silver and iron deposits of southern California.

The combined output of lead, zinc, and copper for the five producing counties of southern California (Inyo, San Bernardino, Riverside, Kern, and Imperial) during 1952 was 10,526 short tons of lead, 5,884 short tons of zinc, and 200 short tons of copper, with a total value of about 5½ million dollars. This constituted most of the lead, more than half of the zinc, and about one-quarter of the copper produced in the State. In 1950, a record year, California ranked eighth as a lead-producing state, and contributed 3½ percent of the national total. Darwin ranked ninth among lead-producing mines, and Shoshone ranked twelfth. In this same year California was eleventh in production of iron, with an output of 831,000 tons that was derived almost wholly from the Eagle Mountains deposit.

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‡ Assistant Mining Geologist, California Division of Mines.

SILVER-LEAD-ZINC DEPOSITS

With a few exceptions, the lead-silver-zinc deposits of southern California are in Paleozoic carbonate rocks that are exposed in areas east of the Sierra Nevada and north and east of the Garlock fault. The only important producing mines are in central and southern Inyo County (fig. 1). Most of the deposits lie within two belts, both of which have the north-northwesterly trend that characterizes the structure of this wedge of the Basin-Range province, and that is parallel to the trend of the Sierra Nevada. One belt extends southward through the Inyo Mountains, the Argus Range, and the northern Slate Range, and includes the Cerro Gordo district, the Santa Rosa mine, and the Darwin district. It is a little more than 100 miles long, although the deposits are small and widely scattered at either end. The other belt, slightly south and offset to the east about 50 miles, includes the Shoshone mines in Inyo County and several small mines and prospects in eastern San Bernardino County. The depleted silver-lead mines of the Panamint silver district, together with other scattered deposits in the Panamint Range, may constitute a lesser belt between the main belts, although the Panamint silver deposits are unique in some respects.

The deposits, except for those in the Panamint silver district, are typical replacements and fissure fillings of lead, silver, and zinc minerals in limestone and dolomite. Mineralization has been controlled by bedding, by fractures, and in some places by igneous contacts. All the deposits have undergone considerable oxidation, and many rich ore bodies have resulted from the preferential concentration of secondary lead, silver, or zinc minerals. At least some primary sulfide mineralization is found in nearly all of the deposits, and in the larger mines it accounts for important ore bodies. The presence of silver in the hypogene ore is generally ascribed to argentiferous galena, although megascopic primary argentite is recorded from some properties. Published reports indicate a silver : lead ratio of between 1 ounce : 3 percent and 1 ounce : 1 percent for most shipments of lead ore. Gold and copper commonly are present in commercial quantities. The most common forms of wall-rock alteration are marmarosis, dolomitization, and silicification.

The general parallelism of the mineral belts and of many of the mineralized structures with north-northwest trend suggests that the mineralizing fluids were influenced by factors that also controlled Basin-Range structure in this area. On the other hand, the mineralization in some of the deposits is known to be older than Tertiary volcanic rocks that are displaced by Basin-Range faults. Evidence for a clear-cut genetic relationship with particular igneous rocks generally is lacking, but the common occurrence of intrusive masses that almost certainly are Nevadan in age, together with the middle to late Paleozoic age of the host rocks along the northwestern belt, suggest that the deposits in this belt, at least, belong to the late Mesozoic metallogenetic epoch. The host rocks at Darwin have been silicated by a Nevadan (?) intrusive mass prior to lead-silver-zinc mineralization. On the other hand, south and west of the Garlock fault, where Nevadan intrusives are abundant to predominant and where the Sierra Nevada trend of structure is less evident or is lacking, base-metal deposits are absent or are trivial in size.

Cerro Gordo Mine. The Cerro Gordo mine is in the southern Inyo Mountains, near the crest of the range, at an elevation of approximately 8,500 feet. It is situated 8 miles by road northeast of the town of Keeler. The geology and mineralization in this area have been described by Knopf (1918), Tucker and Sampson (1938), Merriam (1949), and others. Unpublished reports by R. T. Walker, E. H. Eakland, and Robert Seklemian also have been consulted in the preparation of the following paragraphs.

The Cerro Gordo mine has been in the past one of the principal lead mines of the state, and has been worked intermittently since 1869. Production records are not exact, but it is estimated that the total output from this mine has been about 150,000 tons, including approximately 115,000 tons of high-grade lead-silver ore, 33,000 tons of oxidized zinc ore, and some siliceous silver ore. The early and largest tonnage of lead ore contained about 40 percent of lead with a high proportion of silver. This ore consisted largely of cerussite, anglesite, and galena, with associated bindheimite (hydrous antimonate of lead), tetrahedrite, sphalerite, pyrite, "limonite," and linarite (basic sulfate of lead and copper). Most of the oxidized zinc ore was mined between 1912 and 1919, and contained 35 to 40 percent of zinc with only traces of other metals. It was derived from secondary concentrations of zinc in the footwall parts of the lead ore bodies that had been worked earlier, and consisted largely of smithsonite with minor amounts of hydrozincite, calamine, and calcite. Between 1929 and 1933, production from the Cerro Gordo mine totaled about 10,000 tons with an average content of 0.08 oz. of gold, 28.6 oz. of silver and 39.6 percent of lead. The adjoining Estelle property is reported to have been the source of about 7,000 tons of ore, including 4,000 tons of siliceous gold-silver ore and about 2,700 tons of lead ore containing 21 percent of lead.

The long, narrow Inyo Mountains block trends slightly west of north, and in many places is bounded on both sides by fault zones.

The crest of the range is crossed at a low angle from southeast to northwest by the axis of an anticlinal fold that plunges to the south. In the Cerro Gordo area the range is composed largely of Paleozoic sediments, although on the west flank, between Keeler and the Cerro Gordo mine, Mesozoic rocks occur within a narrow down-faulted syncline. The sediments are transected by numerous north-, northwest-, and east-striking faults. Several miles northeast of the Cerro Gordo property, the Paleozoic rocks are intruded by a large mass of granite. Smaller stocks and dikes of associated rocks occur close to or within the mine workings.

The oldest rocks exposed along the crest of the anticline on the Cerro Gordo property are Devonian beds that are known as the Cerro Gordo limestone. These are the host rocks for the ore bodies of the mine. They consist of limestone, marble, and intercalated beds of quartzite. The Cerro Gordo limestone is overlain by cherty limestone, shale, and fine-grained quartzite of probable Mississippian age, and these rocks in turn are capped by lower Pennsylvanian limestone. Most of the contacts between the various rock groups in the mine area are fault contacts, and the exact thickness of the various units is not known here, although the Devonian rocks probably are more than 1,500 feet thick and the Mississippian (?) sediments are more than 2,000 feet thick.

All of the Devonian and Carboniferous sediments have been intruded near the mine by two small stocks of monzonite porphyry, and within the mined ground by dikes of monzonite porphyry, diabase, and quartz-diorite porphyry, in the order named.

The major structure in the Cerro Gordo area is the highly faulted anticlinal fold mentioned above. Complex local faulting of several ages is evident both on the surface and underground. To the west of the mine shaft, and along the west limb of the anticline, a strong north-south fault zone drops upper Mississippian (?) shale and lower Pennsylvanian limestone down on the west side against older Mississippian beds and the Devonian limestone. This fault, which has been designated the Cerro Gordo fault by geologists of the U. S. Geological Survey, is pre-intrusive and pre-mineral in age, and locally is occupied by a dike of monzonite porphyry. East of the fault, within the Devonian marble, another north-south fracture has localized a diabase dike that has in part controlled the formation of two oreshoots.

The Cerro Gordo fault has been displaced by a series of younger northwest-striking, south-dipping faults. The largest displacement has occurred along the Buena Vista fault, which strikes N. 30° W. and dips about 55° southwest; most of the other faults, which probably are somewhat older than the Buena Vista, strike between N. 50° W. and N. 60° W., and dip more steeply to the southwest. Some of these have localized dikes of quartz-diorite porphyry, and two have been filled with thin quartz-tetrahedrite-galena veins. Intersections between the northwest-striking faults, on one hand, and other faults, the diabase dike, or favorable bedding zones, on the other, have been the main controls for the lead-silver-zinc orebodies. On the lower levels at the south end of the mine, according to Walker (1929), another zone of faults is present. These faults strike northwest, dip northeast, and apparently show evidence of post-mineral movement.

All the orebodies of the Cerro Gordo mine have had the form of irregular chimneys that plunge steeply to the south. All have been rather small in horizontal section, but have been sufficiently rich to make mining profitable. The three largest oreshoots were mined for vertical distances of 550 to 950 feet.

As noted above, the oreshoots occur within the highly fractured and fissured Devonian limestone and marble, and all of the principal orebodies were localized at or near the intersections of northwest-striking faults with north-south faults, fissures, or a diabase dike. In at least one ore chimney, the China Stope orebody, control also was exercised by beds of quartzite in the Cerro Gordo limestone, and by bedding slips in the quartzite.

The concentrations of ore within the Cerro Gordo area thus can be ascribed to a series of favorable conditions that included (1) the intrusion of quartz monzonite stocks and associated dikes, (2) the presence of Devonian limestone and marble, and (3) intense pre-mineral fracturing and faulting, which shattered the Devonian rocks and formed conduits for ore-bearing solutions.

*Santa Rosa Mine.** The Santa Rosa property is about 10 miles south-southeast of Cerro Gordo, at the southern end of the Inyo Mountains. Total production from the mine since 1911 amounts to 36,854 short tons of ore containing 11,990,792 pounds of lead, 487,347 pounds of copper, 4,105 pounds of zinc, 426,543 fine ounces of silver, and 478.7 fine ounces of gold (MacKevett, 1953, p. 4).

The host rock is Permian (?) silicated limestone that crops out in an area approximately 2,000 feet long and 600 feet wide. This area is entirely surrounded by Tertiary and Quaternary (?) volcanic tuff and flows of basalt (MacKevett, 1953). The sediments within this inlier strike northward and dip from 0 to 60 degrees eastward. They appear to represent a part of the east limb of the large, southward-plunging anticline that is exposed along the crest of the Inyo Mountains near the Cerro Gordo mine.

The ore is largely confined to a series of north-trending fissures and shear zones that dip 30 to 80 degrees west. Steep, north-northeast-trending dikes of basalt intrude both the limestones and the

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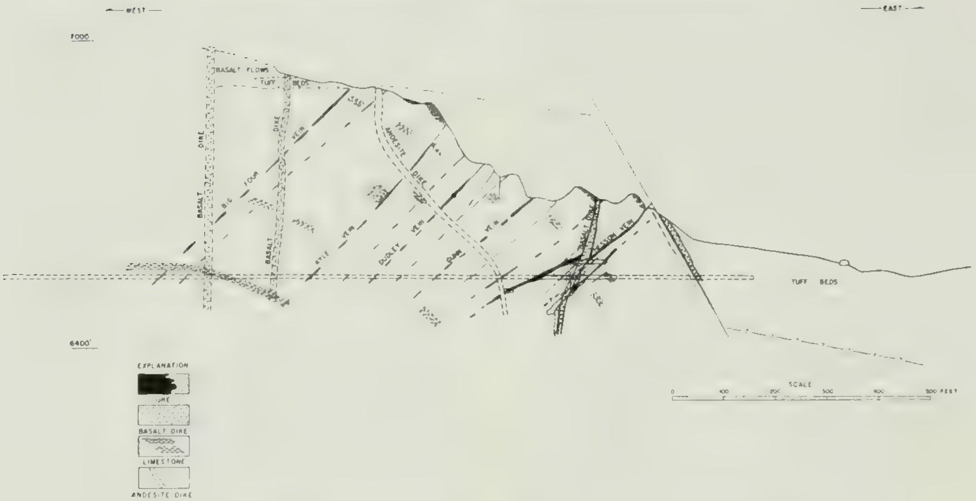

Figure 2. Cross section of the Santa Rosa mine, Inyo County. *After R. Seklemian, 1952.*

lowest exposed volcanic rocks, and they cut and offset very slightly the mineralized shear zones. Mineralization consists mostly of oxides but with some galena, and occurs along the contacts of some of the dikes. The ore tends to be thickest at the intersections of the dikes with the shear zones (fig. 2). Inasmuch as these dikes presumably were feeders for some of the basalt flows, it has been suggested that the mineralization at the Santa Rosa mine either is related to them or is of later origin. It seems more likely, however, that mineralization was pre-basalt in age, that it was localized along the shear zones and particularly at their intersections with north-northeast-trending fractures, and that subsequent occupation of these fractures by the basalt dikes may have resulted in some remobilization of the ore minerals.

Three steeply dipping, northwest-trending dikes of syenodiorite porphyry cut the silicated limestone and the veins, but are themselves cut by the basalt dikes. MacKevett (1953, p. 5) notes that similar dikes in nearby areas are "considered to be of Cretaceous (?) age, although they may be as young as Tertiary or as old as Jurassic." The easterly edge of the limestone inlier is along the Santa Rosa fault, which is at least in part younger than the basalt dikes.

According to MacKevett (1953, pp. 8-9), "The unoxidized vein material, studied in polished sections of ore from the primary veins in the Jack Gunn workings, consists mainly of galena, moderate amounts of pyrite and sphalerite, small amounts of chalcopyrite, and very minor amounts of supergene copper minerals. . . . Cerussite is the commonest secondary ore mineral and limonite is the most abundant secondary gangue mineral." Thirteen other secondary minerals are listed.

*Darwin Mines.** Darwin is now † the largest producer of lead, silver, and zinc in California. The district is in the Darwin Hills, 5 to 10 miles south of State Highway 190 and about 24 miles south-southeast of Cerro Gordo. It was discovered in 1874, and was depleted of its rich surficial oxide ores within a period of five or six years. During this time the population of Darwin had mushroomed to 5,000. The district is estimated to have yielded ores valued at about $3,000,000 prior to 1900, and additional ores valued at perhaps $4,000,000 between 1900 and 1945. The Anaconda Copper Mining Company purchased the major producing mines in 1945, and obtained ores valued at approximately $18,000,000 during the period 1945-1953. The present daily mill capacity is 150 tons of oxide ore and 300 tons of sulfide ore. Direct shipping ore also is mined at a rate of about 25 tons per day.

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† The mines were shut down in February 1954, after preparation of this paper.

The geology and mineral deposits of the district have been studied by Knopf (1914), Kelley (1937, 1938), Wilson (1943), Davis and Peterson (1949), and others. The sedimentary rocks that underlie the Darwin Hills are Pennsylvanian in age, and include pure and impure limestone, quartzite, and shale. They have been deformed and intruded by the Coso granite batholith, by a granodioritic stock, and by numerous sills and dikes that range in composition from granite to gabbro. As at Cerro Gordo and Santa Rosa, folding in the sedimentary rocks has a northerly to northwesterly trend, and the axis of a major northwestward plunging anticline lies near the crest of the Darwin Hills. Minor folds on the flanks of this anticline appear to have had a significant influence in localizing the ore bodies, especially those that occur along bedding in the sediments.

Intrusion of the elongate granodiorite stock for an exposed distance of about 5 miles, mainly along the core of the major anticline, was accompanied by development of a hornfels and tactite aureole as much as 2,500 feet wide. Locally this silication appears to be related to sills, and some feldspathization has taken place at the contacts. Subsequent deformation has produced three main fracture sets: one strikes N. 50° to 70° E., shows very little displacement, and commonly is mineralized; a second strikes N. 10° to 40° E., and is both pre- and post-mineralization in age; and a third strikes N. 60° to 75° W., and includes the large left-lateral Darwin tear fault at the north end of the district.

The principal ore bodies occur in a zone just west of the granodiorite stock (fig. 3). In order of importance, the ore bodies are: (1) bedded replacements that commonly are more or less localized along anticlinal flexures, and lie near but not in contact with the intrusive sills; (2) irregular replacements of the silicated limestone along fissures; and (3) fissure fillings. In addition, several bodies of tungsten ore occurred in the district. One of these amounted to several hundred tons, and contained 10 to 15 percent of WO_3. It was

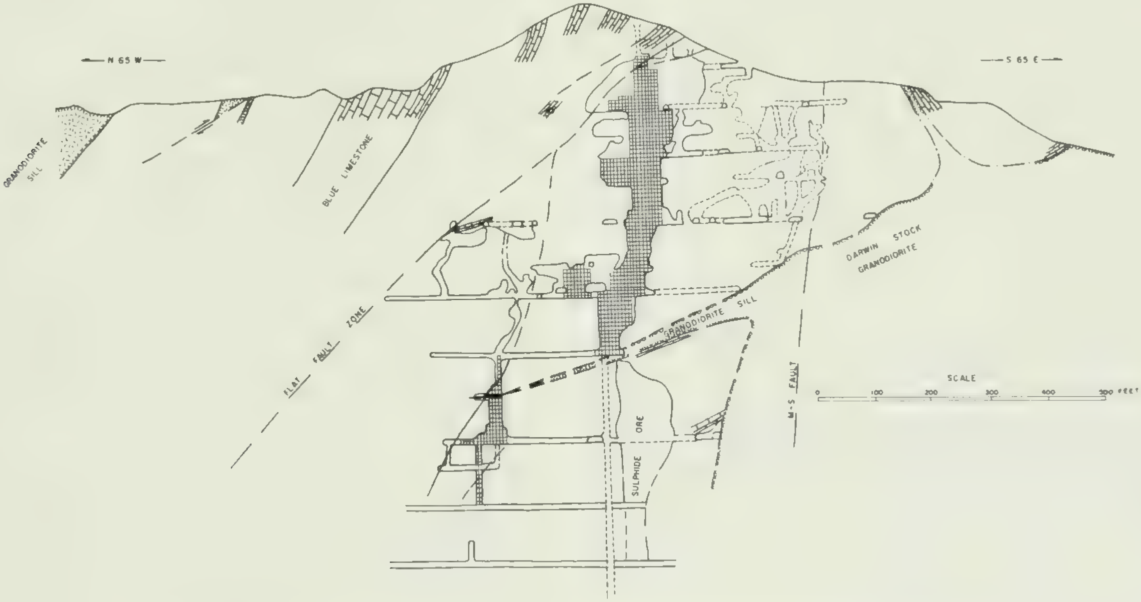

FIGURE 3. Longitudinal section of the Essex ore zone, Darwin mines. *After Davis and Peterson, 1949.*

found at one end of a stope in high-grade oxidized lead-silver ore. The scheelite, which shows many excellent crystals, is embedded in a matrix of iron oxide, jarosite, and clay, and is thought to have been formed during an earlier period of mineralization and silication.

The hypogene sulfide minerals clearly replace the lime-silicate minerals of the tactite. Galena and sphalerite are the major sulfides, and chalcopyrite, tetrahedrite, pyrite, bornite, chalcocite, and covellite are minor to very minor primary sulfides. Cerussite, anglesite, plumbojarosite, sooty argentite, and cerargyrite are the principal oxidized ore minerals, and calcite, fluorite, quartz, jasper, iron oxides, clays, sulfur, gypsum, jarosite, and hydromica are common in the gangue along with the garnet, wollastonite, diopside, epidote, and other lime-silicate minerals of the host rock. In addition, psilomelane, melanterite, creedite, goslarite, wulfenite, vanadinite, linarite, caledonite, hydrozincite, pyromorphite, brochantite, azurite, hemimorphite, and malachite have been identified.

Northern Argus Range. Zinc Hill, at the north end of the Argus Range about six miles northeast of Darwin, and the Modoc district, on the east flank of the Argus Range about 10 miles east of Darwin, are two lesser districts that belong in the northern mineralized belt. At least three of the properties in this area have a total production with value exceeding $1,000,000. In both districts the ores, both oxidized and primary, occur mainly as replacements controlled by fractures and bedding in late Paleozoic limestone. The Defense mine in the Modoc district is of interest for the rare mineral coronadite ($MnPbMn_6O_{14}$), which here constitutes an ore of lead along with galena and its oxidized products.

Panamint Silver District. The small Panamint silver district (Murphy, 1930) lies near the crest of the Panamint Range about 4 miles south of Telescope Peak. It was largely worked out between 1873 and 1877. The bulk of its rich silver ore occurred in steep northwestward and northeastward trending quartz veins in carbonate rocks and some clastic rocks of early Paleozoic age. Primary sulfides include freibergite, galena, sphalerite, pyrite, and chalcopyrite. Oxidation is unimportant, in contrast to the relations in the other districts of southeastern California. The district has been of recent interest for small amounts of scheelite that have been recovered from the dumps.

Other deposits in the Panamint Range are similar to those of the westerly and easterly belts of lead-silver-zinc mineralization.

*Shoshone Mines.** The Shoshone mines are on the west flank of the southern Nopah Range about 7 miles east of Tecopa. The property is a consolidation of several mines, the ore bodies in which occur along a single structure, the Shoshone fault vein, which has been offset by postmineral faulting. Prior to 1947 some 250,000 tons of ore with a gross value of more than $5,000,000 had been mined, and more than half of this was produced between 1912 and 1928. The Anaconda Copper Mining Company purchased the properties in 1947, and since that time has produced more than 160,000 tons of ore containing approximately 40,000,000 pounds of lead, 6,000,000 pounds of zinc, 870,000 ounces of silver, and 15,600 ounces of gold. One-third of the output has been high-grade shipping ore with an average metal content of 27 percent lead, 11 ounces of silver, and 0.20 ounce of gold. Nearly all of the ore is highly oxidized, and consists predominantly of cerussite and anglesite, with associated iron oxides, smithsonite, calamine, linarite, caledonite, and some residual galena. Sulfide minerals include galena, pyrite, and sphalerite, with very minor amounts of seligmannite and chalcopyrite.

The ore zone extends for a distance of more than 3 miles along the east flank of a structural ridge, the crest or core of which is composed of Archean granite-gneiss. This gneiss crops out along the base of the Nopah Range and also forms the outlying hills on the western slope. It is overlain to the east by a thick succession of northwest-striking, east-dipping sediments of Algonkian and Lower Cambrian (?) age. These rocks compose the eastward-tilted block that makes up the Nopah Range itself, and include 0 to 1,000 feet of Algonkian dolomite, shale, and chert; the Noonday dolomite, about 1,100 feet of massive to well-bedded dolomite overlain by about 400 feet of sandy and shaly dolomite (the Shoshone member in figure 4); the Johnnie formation, mainly interbedded quartzite and sandy dolomite, with some shale; the Stirling quartzite; and the Wood Canyon formation. The beds are offset by several cross faults, and are repeated or cut by the strike fault that is the important ore-bearing structure. The Noonday dolomite is the country rock in nearly all of the ore bodies, although ore also occurs along the Shoshone vein system and other fissures in the Johnnie formation, and one mineralized quartz vein is exposed within the gneiss.

At the War Eagle mine, the Shoshone fault vein strikes about N. 25° W., roughly parallel to the formational trend, and dips eastward at 30 to 50 degrees. It is less steep than the bedding in the adjacent rocks. It is a normal fault that is rather complex in detail, and has a dip-slip displacement of more than 700 feet. Distinctly younger is a series of east-west faults, which generally dip to the south and show normal displacements. Movement on these faults was followed by post-mineral displacements on fissures that strike northeast and dip 45 to 70 degrees northwest. These fissures in turn are displaced by a few northwest-striking faults that dip 30 to 70 degrees southwest. The latter two fault sets may follow pre-mineral

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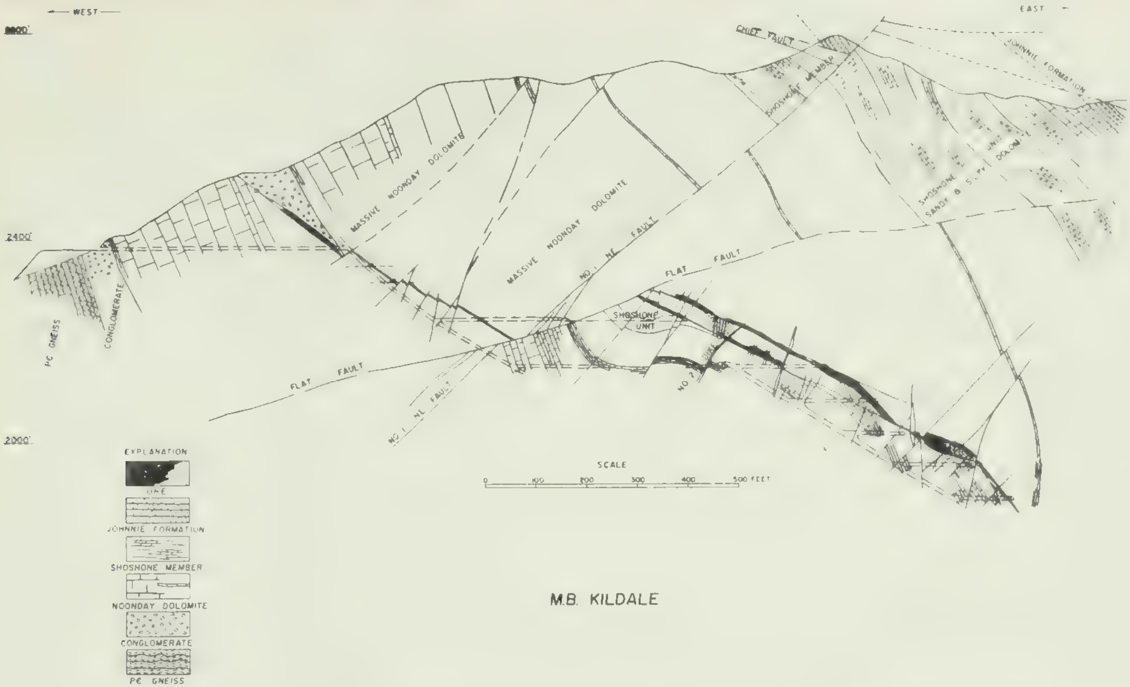

FIGURE 4. Cross section of the War Eagle mine, Shoshone district.

shears, although the major movement on them is post-mineral in age. The ore is controlled locally along the Shoshone fault vein by intersecting fractures that strike parallel to one or the other of these fault sets. Proximity to pre-fault flexures and an abundance of northeasterly cross fractures and faults (fig. 4) appear to have been favorable conditions for ore formation.

Eastern San Bernardino County. A dozen or more small mines and prospects make up the southern end of the eastern mineralized belt. Of these, larger representatives are the Silver Rule ore body in a shear zone in Noonday dolomite, and the Mohawk deposit in limestone along a faulted contact with quartz monzonite. The Carbonate King zinc mine, on Kokoweef Peak about 5 miles southeast of Mountain Pass, is unusual in that the ore is dominantly calamine with some smithsonite and minor hydrozincite, sphalerite, and galena. About 6,200 tons is reported to have averaged 34.2 percent of zinc, 1.0 percent of lead, and 9.8 ounces of silver. The ore bodies occur more or less along bedding in Monte Cristo limestone of Mississippian age.

Black Jack Mine, Santa Catalina Island. Completely unrelated to any other known important lead-silver-zinc mineralization in southern California are the vein deposits on Santa Catalina Island (Tucker, 1927). The largest deposit, at the Black Jack mine, is a vein that contains sphalerite, galena, and pyrite. This vein occurs in a belt of Franciscan hornblende schist. The mine was operated from 1925 to 1928, during most of which time the ore was treated in a 100-ton flotation plant on the island.

IRON DEPOSITS

Unlike the lead-silver-zinc deposits described in the preceding paragraphs, all but one of the larger iron deposits of southern California lie south of the Garlock fault in areas where Nevadan intrusives are abundant and where the Sierra Nevada trend of structure is absent

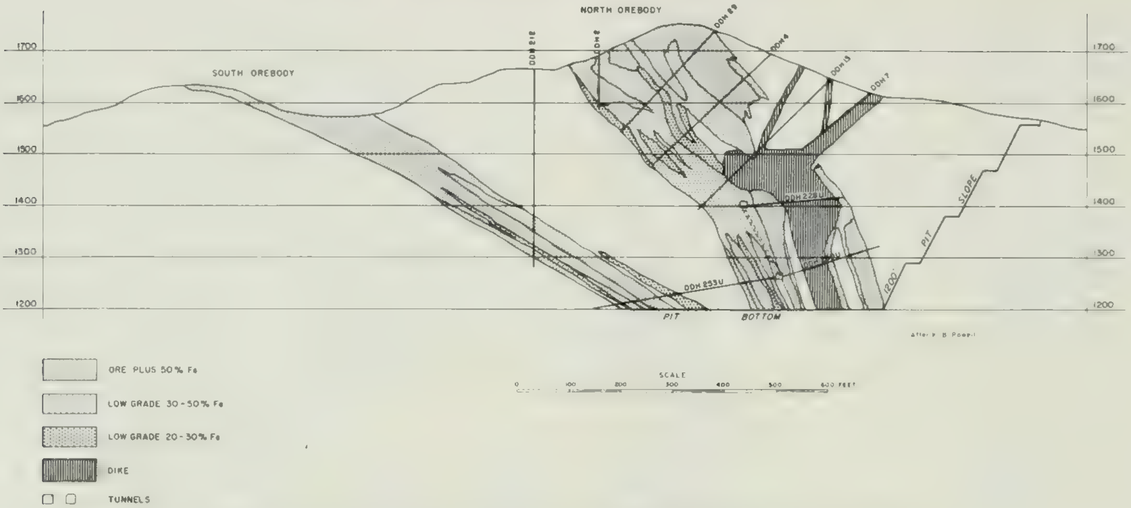

FIGURE 5. Section through the North-South ore bodies, Eagle Mountain iron deposit.

or poorly defined. The one exception is the Beck deposit, which lies in the Kingston Range along the trend of the eastern lead-zinc belt in northeastern San Bernardino County.

The principal iron deposits or districts in southern California have been described by Lamey, et al. (1948). These include: (1) the Beck deposit, (2) the deposits now being exploited by the Kaiser Steel Corporation in the Eagle Mountains, Riverside County, (3) the Bessemer or Lava Bed district, (4) the Silver Lake district, (5) the Old Dad Mountain deposit, (6) the Cave Canyon deposits, (7) the Vulcan deposits, (8) the Iron Hat deposits, and (9) the Ship Mountains deposit. All but the Beck and Eagle Mountains deposits are in San Bernardino County (fig. 1). Summary statements on several of the deposits also are contained in a recent report on San Bernardino County (Wright, et al., 1953).

All of the larger deposits are contact-metamorphic replacements in Paleozoic or pre-Cambrian limestone and dolomite, and are genetically related to nearby granitic intrusive rocks. Magnetite and hematite are the chief ore minerals; the hematite is secondary, and in most deposits is subordinate. The ore bodies in the Silver Lake district are unusual in that they are "thought to consist of material that was derived from a contact-metamorphic deposit, redeposited as a rubble or talus on an eroded sandstone surface, and perhaps brought to its present situation by thrust faulting" (Lamey, 1948, p. 42). In the Ship Mountain deposit, the Iron Age deposit (Wright, et al., 1953, p. 95), and in other small deposits the ore, chiefly hematite with subordinate magnetite, has filled fissures and brecciated zones in the igneous and metamorphic host rocks.

These iron deposits have been the subject of considerable interest since early in the century, but little production of iron ore resulted until 1942, when the Kaiser Steel Corporation began mining at the Vulcan deposit. This was worked until July 1947, and yielded 2,643,000 tons of ore for blast-furnace feed at the Kaiser steel plant in Fontana. The Cave Canyon mine has been the second largest source of iron ore in San Bernardino County, and the ore has been used in the manufacture of cement. Properties in the Bessemer area probably have yielded less than 50,000 tons of ore, and others in the county have a combined total output of less than 10,000 tons up to 1953. In the spring of 1953, the deposits in the Silver Lake district were opened up as a temporary supplemental source of iron ore for the Kaiser plant. The Beck deposits in the Kingston Range remain among the largest unworked sources of iron ore in southern California.

Eagle Mountains Deposits. The most important deposits of iron ore in southern California are those of the eastern Eagle Mountains, in Riverside County, and are being exploited by the Kaiser Steel Corporation. The first consolidation of claims covering these deposits was made in 1890, and in 1908 the entire group, comprising more than 100 claims, was purchased by E. H. Harriman of the Union Pacific Railroad. No ore was mined until 1948, when the Kaiser Steel Corporation, which had purchased the property in 1946, started open-pit mining in the Bald Eagle deposit. This pit had nearly reached the planned depth by November 1953, and had yielded 3,800,000 tons of ore with an average grade of 53 percent iron. The pit in the North and South orebodies was opened in July 1952, and by November 1953 had yielded about 2,000,000 tons of ore with an average grade of 54 percent iron. The proved reserves in this deposit will meet the ore requirements for the three blast furnaces of the Fontana plant, each with a capacity of 1,200 tons of hot metal per day, for the next 25 years. This reserve ore has an average grade of 50.7 percent iron.

More than 60 orebodies, ranging from less than 100 feet to more than 1,000 feet in strike length, are exposed along a mineralized zone that trends east-west for a distance of more than 6 miles along the northern part of the Eagle Mountains. This zone ranges in width from a quarter of a mile to 1¼ miles. The orebodies now being mined are in the eastern end of this zone.

In this general area, two beds of early Paleozoic dolomite, lying discordantly and separated by 50 to 250 feet of quartzite, were folded into a broad anticline with an east-west axis. Contact metamorphic action accompanying the intrusion of quartz monzonite resulted in partial or complete replacement of the dolomite and of some of the impure quartzite by iron ore and associated silicate minerals (see Campbell, Contribution No. 6, Chapter VII). The anticlinal structure of the rocks has been complicated by considerable faulting, and some vertical displacements are as great as 300 feet. The crest and south limb of the anticline have been completely eroded (fig. 5). The Bald Eagle orebody consists mainly of the stratigraphically lower ore bed. The North and South orebodies are in the upper and lower beds, respectively, and lie about 800 feet east of the Bald Eagle pit.

The ores of highest grade are hard, fine-grained hematite and coarsely crystalline magnetite. The lower-grade ores include (1) mixtures of hematite and magnetite, with disseminated calcium and magnesium silicates, and (2) tremolite or serpentine with irregularly disseminated magnetite, or, less commonly, hematite. Magnetite is the primary ore mineral, and is accompanied by some pyrite. The pyrite appears only in the deeper parts of the orebodies, or in unshattered blocks of rock, and is represented at the surface by jarosite and limonitic material.

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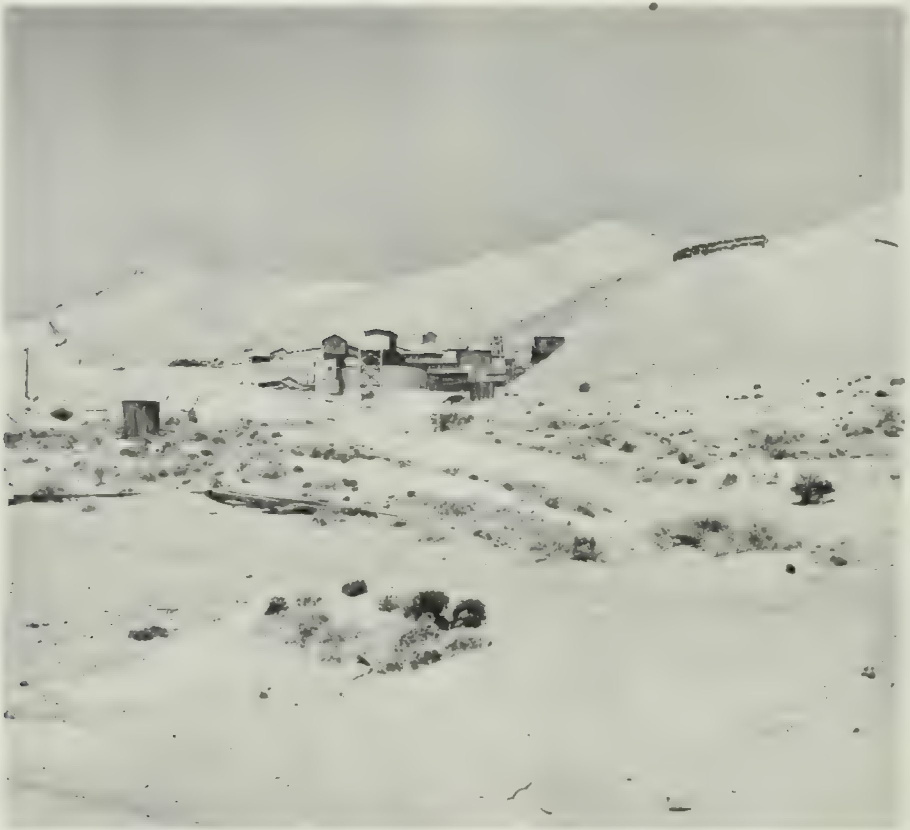

FIGURE 6. Surface plant at Darwin Mines, 1954. *Photo by Mary R. Hill.*

6. GOLD AND SILVER MINING DISTRICTS IN THE MOJAVE DESERT REGION OF SOUTHERN CALIFORNIA

By Dion L. Gardner *

INTRODUCTION

Deposits valuable for their gold and silver content are dispersed throughout the desert area of southern California. They are localized in many mining districts, and are separated by areas from which little or no production has been obtained. Large parts of such areas are underlain by essentially barren granitic rocks. Elsewhere deposits may remain undiscovered because they occur on pediments with few bedrock exposures, or are hidden beneath post-mineral volcanic rocks or continental sedimentary rocks.

The mining districts are localized near major faults, and are associated with intrusive rocks correlative with the late Mesozoic Sierra Nevadian granitic rocks, with late Cretaceous (?) or early Tertiary (?) intrusive rocks, or with post-middle Tertiary volcanic plugs and other throat rocks. Some of the volcanic rocks and the mineralization associated with them probably are as young as Pliocene. No attempt will be made here to discuss completely all the mines or districts, and the geologic generalizations in the following pages are accompanied only by descriptions of some noteworthy examples of productive mines and ore bodies.

Permission to incorporate geologic data has been granted by Burton Mines, Inc. (owners of the Tropico mine), Desert Acres, Inc. (owners of the Cactus mine), and Frank Royer (owner of the Kelly mine). Thoughtful conversations with Drs. J. A. Noble and D. F. Hewett, and with Messrs. Frank Royer, Clifford Burton, Edward Atkinson, and others have helped in the development of this paper. However, the writer assumes full responsibility for the ideas presented herein.

HISTORICAL SKETCH

Although turquoise previously had been mined by Indians near Baker, gold had not been produced, so far as is recorded, prior to 1780 or 1781 in southern California, when the Spaniards mined placer and residual gold in the Cargo Muchacho district on the southeastern border of Imperial Valley. Even before the historic discovery of gold in northern California, Mexicans mined gold on a small scale from placer gravels in Placerita Canyon north of Los Angeles. The gold rush of 1848 and 1849 subsequently spread over southern California, and in 1851 gold was found at Greenhorn Gulch near Kernville. Later locations were made in the Keysville district and Cove district of Kern County, and also in areas near Big Bear in San Bernardino County, and Julian in San Diego County. A quiescent period was followed by a revival of interest in 1865, immediately after the Civil War, and by another revival during the depression of 1892. These resulted in the discoveries of the Rand, Mojave, Tropico, Clark Mountain, Goodsprings, Sunshine Peak, Twentynine Palms, and Silver Hills districts, as well as many others. Many of the productive mines and most of the prospects were discovered during these periods of activity.

A major find since the turn of the century was developed into the Kelly silver mine at Red Mountain, near Randsburg. This accidental discovery, made in 1919 in a district which earlier had seen both a gold and a tungsten boom, resulted in a very large production of high-grade silver ore for the ensuing few years.

The depressions of the early 1920's and 1930's brought favorable conditions for silver and gold mining, and prospecting was again stimulated. On Soledad Mountain, near Mojave, the Golden Queen deposit was found and extensions of other mines were developed. The most recent find in this area was the Cactus deposit, at Middle Buttes, which in 1938 and 1939 was the principal source of silver in California. During this period an ore body also was found in the Cargo Muchacho district.

Almost all gold mining was stopped in 1942 by the War Production Board Limitation Order L 208, and most of the mines then active have not been reopened. The Bagdad Chase mine near Ludlow continued to operate because its siliceous ore was needed in the Arizona smelters. The largest gold mine now active in southern California is the Tropico near Rosamond. The owners of this mine, Burton Brothers, Inc., also operate a custom mill at Rosamond. Leasing, prospecting, and small-scale operations are in progress elsewhere, but appreciable production of gold and silver must wait on either lower costs or an increased price that will enhance the reward and hence revive interest in prospecting and mining.

GOLD AND SILVER DEPOSITS

The gold and silver deposits of southern California are divisible into the following categories based on age, type, rock, and mineral associations: (1) hypothermal gold veins, (2) mesothermal gold-copper veins, (3) gold and silver deposits related to Upper Cretaceous (?) or Tertiary (?) granite, and (4) epithermal gold and silver deposits related to middle and upper Tertiary intrusive rocks.

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Hypothermal Gold Veins. The districts of Keysville, Cove, Kernville, Acton, Neenach, San Gabriel, Julian, and Cargo Muchacho probably represent a southern extension of Mother Lode type of mineralization, which is associated with the Sierra Nevadian revolution. Various deposits in the Mojave Desert region are believed to be genetically related to intrusive bodies contemporaneous with the Sierra Nevada batholith. Most are associated with masses of granite or diorite that are intrusive into Paleozoic (?) metasediments. The deposits characteristically occur in lenses or veins of massive quartz that contain free gold, pyrite, arsenopyrite, and minor chalcopyrite. These veins lack the epithermal character and rhyolitic associations of the Tertiary veins. Some of them have been reopened and mineralized at later periods.

The Cargo Muchacho district, near Ogilby in the southeastern corner of the State, has been described by Henshaw (1942, pp. 163-196). The mineralization occurs in flat veins along east-west thrust (?) faults, and is believed to be late Mesozoic in age. The veins, which contain gold with pyrite and minor copper, appear to be similar to others in the desert to the north.

Mesothermal (?) Gold-Copper Veins. The Ludlow (Stedman) district contains the principal examples of mesothermal gold-copper veins in southern California. The veins are in a quartz porphyry, and contain gold and secondary copper minerals. The chief operation is the Bagdad Chase mine south of Ludlow. The veins are large, continuous, and strongly mineralized. The shoots are smaller, and are localized by structural traps. Faulting is complex, is represented chiefly by low-angle, strike-slip breaks, and is pre-, inter-, and post-mineralization in age.

Gold and Silver Deposits Related to Upper Cretaceous (?) or Tertiary (?) Granite. The writer believes that much of the gold and silver mineralization in southern California is genetically related to a biotite granite intruded in the interval between the period of Mesozoic mineralization (Jurassic ?) and the later period of Tertiary mineralization that is associated with rhyolitic or dacitic plugs and volcanoes. However, the evidence for this is far from conclusive. This granite is difficult to recognize, for it is similar in appearance and mode of weathering to a widespread biotite granite that is older, and may resemble either marginal or alteration phenomena of this intrusive. Moreover, it may occur in areas of later mineralization, and may even occur as dikes in the same or parallel openings that survived as channelways for later mineralization.

At Tropico Hill, near Rosamond, a 3-foot dike of what appears to be this granite occurs along parts of the vein zone. Here later Tertiary mineralization in the zone makes it impossible to determine the part played by this granite. It may be solely an early-stage alteration phenomenon. The same or a similar granite occurs in the Rand district, where it appears in the footwall of the Union tungsten-bearing vein at Atolia.

Epithermal Gold and Silver Deposits Related to Middle and Upper Tertiary Intrusive Rocks. Epithermal veins containing gold and silver are distributed from the Mojave area (Middle Buttes, Soledad Mountain, Tropico Hill) eastward to Randsburg, to the Calico district near Barstow, to the Clark Mountain area, and even to the Oatman district in Arizona. The veins occur within or near centers of intrusive volcanic rocks that exist mainly as dikes and plugs. The gold and silver are present in different proportions from mine to mine and even from place to place in the same ore shoot.

Veins of this type characteristically contain quartz, calcite, or both of these minerals. The minerals typically were formed in several stages, and range in texture from drusy to fine-banded. Adularia is present locally. Free gold and sparse to abundant pyrite occur in local shoots along persistent vein zones. The gold contains admixed silver; the fineness is commonly about 800, and in some deposits is as low as 300. The silver occurs as electrum or as a sulfide, and in variable proportions. Cerargyrite, argentite, proustite, and sparse lead and zinc minerals with their secondary products are found in many deposits. High proportions of antimony and arsenic are associated with the ores. Cinnabar occurs locally. At some localities, particularly in the Randsburg district, scheelite occurs in or near the gold- and silver-bearing veins.

The ore-bearing parts of many of the veins are confined to pre-Tertiary ''basement'' rocks, and are either parallel to or near dikes or other masses of rhyolitic rock. In the vicinity of such deposits mineralization commonly extends into a less competent cover of Tertiary rocks, but ordinarily is much less pronounced there than in the ''basement'' rocks. Some of the deposits, such as those at the Cactus mine, are localized near a contact between granite and rhyolite. Others, like those at the Tropico and Mojave mines, are developed within intrusive rhyolite or rhyolite breccia.

The ore shoots vary greatly in size and show a pronounced structural control. Fault traps, intersections of fractures, changes in strike or dip, and closures in plan or section are bounding features. The major control is faulting that has repeatedly opened individual veins to ore-forming solutions. The degree to which the vein zones could be permeated by solutions carrying gold or silver was the dominant factor that localized the ore shoots. In some deposits the solutions appear to have moved horizontally rather than vertically. Solutions probably were initially acid, for sericitization, kaolinization, and alunitization are characteristic and locally are prominent. Alu-

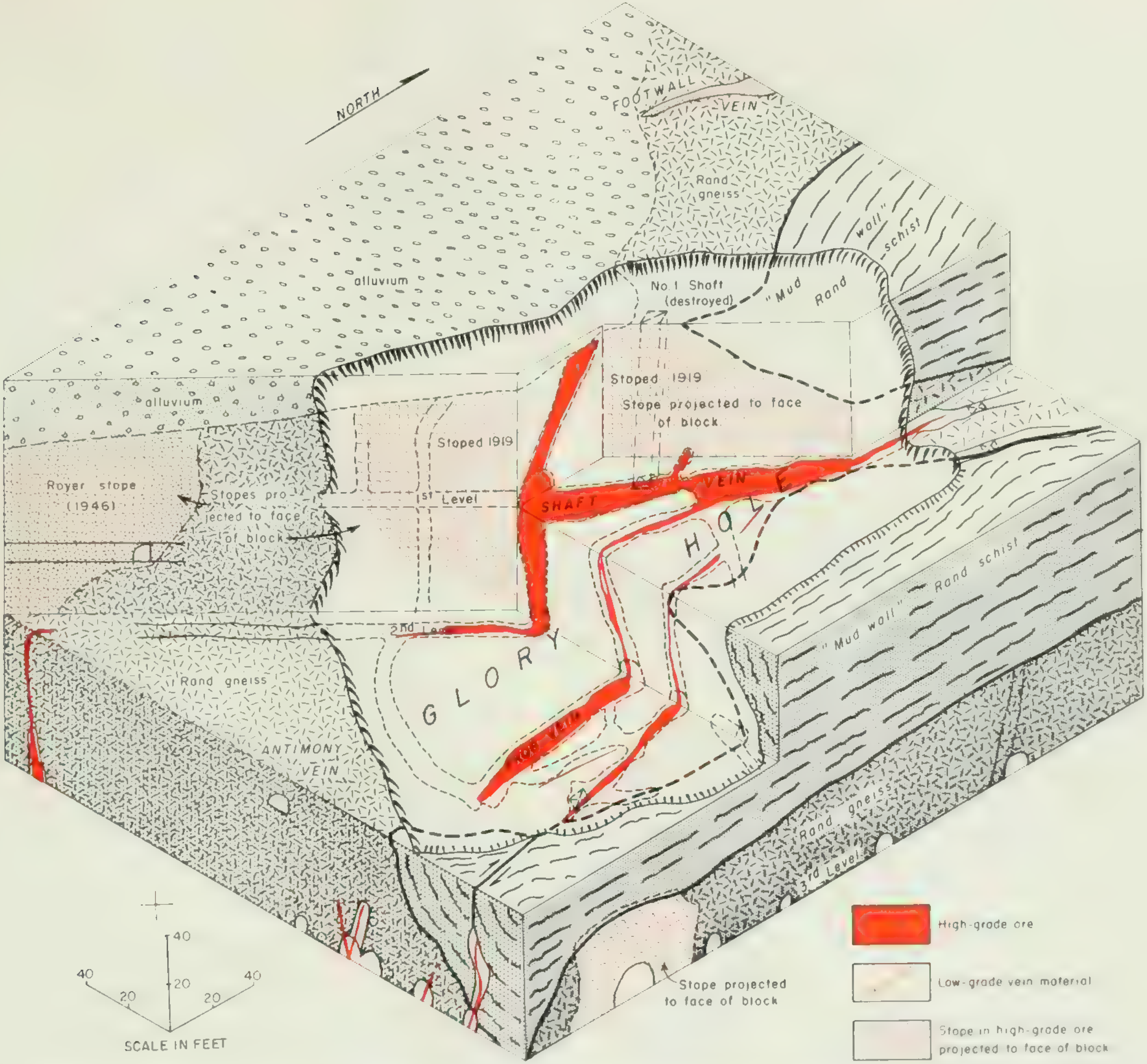

Figure 1. Isometric diagram of the Kelly glory hole, Kelly silver mine, San Bernardino County, California. These workings yielded 55,338 tons of ore valued at $3,580,000.

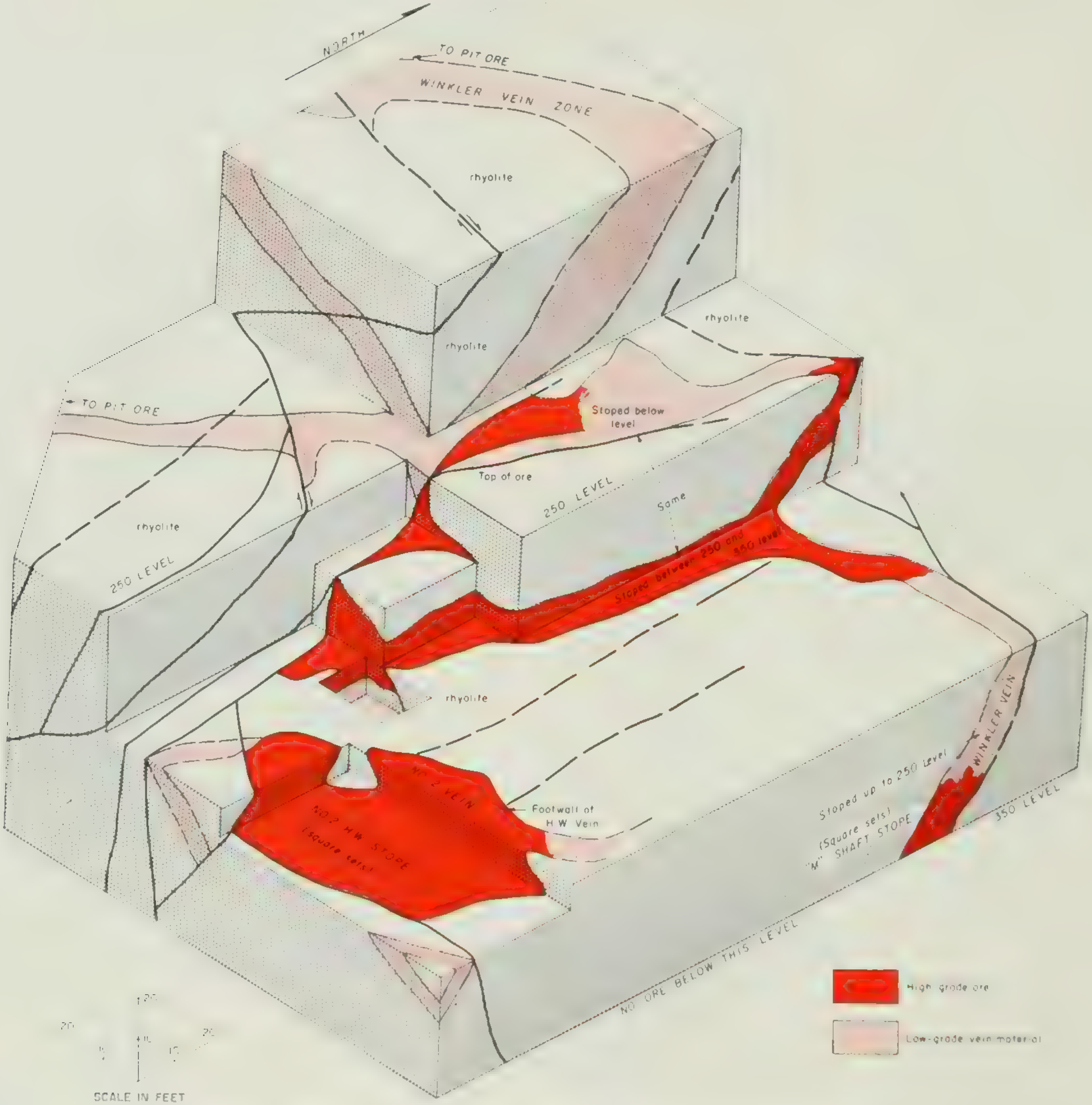

FIGURE 2. Isometric diagram of the Winkler ore bodies, Cactus mine, Middle Buttes, Kern County, California.

nite and kaolin are major constituents of some of the ore at the Middle Buttes deposit. The presence of later calcite (commonly manganiferous) and scheelite indicates a change from acid to alkaline solutions during ore deposition in some localities.

DISTRICTS AND DEPOSITS

Randsburg District. The Randsburg district was investigated and described thirty years ago by Hulin (1925a, 1925b). Subsequent development and study of the mines have amplified our knowledge of the district, but have prompted no major change in Hulin's ideas. The district also has been described in reports of the California Division of Mines (Tucker, Sampson, and Oakeshott, 1949; Wright, Stewart, Gay, and Hazenbush, 1953).

An important group of ore bodies has been worked in the Kelly silver mine, and some of their relations are shown in the isometric diagram of plate 2. The mine area contains two sets of veins in the pre-Cambrian (?) Rand schist. These consist of linked, torsional north-trending veins between roughly parallel veins that trend northeast and dip southeast. Bodies of high-grade ore have been localized below a fault, known as the "Mudwall," that dips gently north. The ore bodies rake to the northeast. The "Mudwall" appears to be a pre- and inter-mineral fault-vein that lies along the hanging-wall side of a schist septum in a body of monzonite. En-echelon continuations to the northwest also contain gold, and are cut by diabase dikes.

Overlying lake beds of Tertiary age have been brought into contact with the monzonite by a fault that may be in part a thrust. The lake beds are silicified, mineralized, and intruded by rhyolite that is probably related to the magmatic source of the mineralizing solutions. These solutions apparently moved upward and southward to fault traps and torsionally opened fractures. Ore bodies on the 19th and deepest level, about 1,500 feet beneath the outcrop, contain good values in gold but have not been stoped. The silver, which is more abundant at higher levels, appears to have been formed later than the gold.

The Kelly mine is noted for the concentration of unusually high-grade ore in relatively small bodies (fig. 1). This feature can be attributed, at least in large part, to a nearly perfect closure of the "Mudwall" and to repeated reopenings and long-continued mineralization along the same vein system. A contour map of the footwall side of the "Mudwall" shows that the ore bodies are concentrated in upward swells of the original fault, and in veins localized beneath these swells.

Middle Buttes. The Cactus mine lies west of Mojave and on the western flank of Middle Buttes, which is a complex plug of rhyolite that crops out over an area of about 3 square miles. Several types of rhyolitic rocks are present, and a contact with older granite is exposed along the western side of the plug. Kaolinization, silicification, pyritization, and late alunitization occur throughout the plug. Most of the mine workings lie along the Cactus vein, which has been explored for a distance of 4,000 feet along the western flank of the hill adjacent to the contact with granite. These workings have been developed in two ore bodies that are rich in silver. The ore occurs in vein zones trending N. 30° E. and dipping gently to the southeast. The Cactus ore shoot was explored and mined to the 10th level; it rakes at a low angle to the east, and has been mined continuously for a distance of about 900 feet. The better ore did not crop out, and extensions are probable.

The Winkler vein zone was found about 1,500 feet southeast of the Cactus vein. The Pit ore body, which cropped out at the surface, was mined first. Ore also was found in two bodies that were blind, and showed only small quantites of low-grade ore in their higher parts. The isometric diagram (fig. 2) of the top of one of these ore bodies shows the manner in which the high-grade ore terminated upward, and illustrates the close structural control.

The "M" shaft ore was not continuous with the north ore lens on the 250 level, although the shoots were on the same vein. The discontinuous high-grade shoots are relatively small, but some are as much as 100 feet long and 10 to 15 feet wide.

The ore in the mine is of two types:

(1) Kaolinized rhyolite broken and interlaced with jarosite and goethite (?) that form a red gouge with gold. This ore contains little alunite or quartz.

(2) Strongly kaolinized rhyolite with abundant pink alunite, minor quartz, and traces of manganese. Free gold occurs as dust or powder, and rarely as larger, though still minute, particles.

Mojave District. The most publicized of the later discoveries in the Mojave district was that of the Golden Queen, which for several years was a large producer. Numerous smaller ore bodies also have been mined in the district. In figure 3, cross sections through the Whitmore mine show relations that are typical of the district. In this property, a northwest-trending, gently dipping, linked vein has been mineralized between two north-trending veins. The vein consists of relatively pure calcite, manganiferous calcite, and minor quartz, and contains values in gold and silver over good widths. There may be

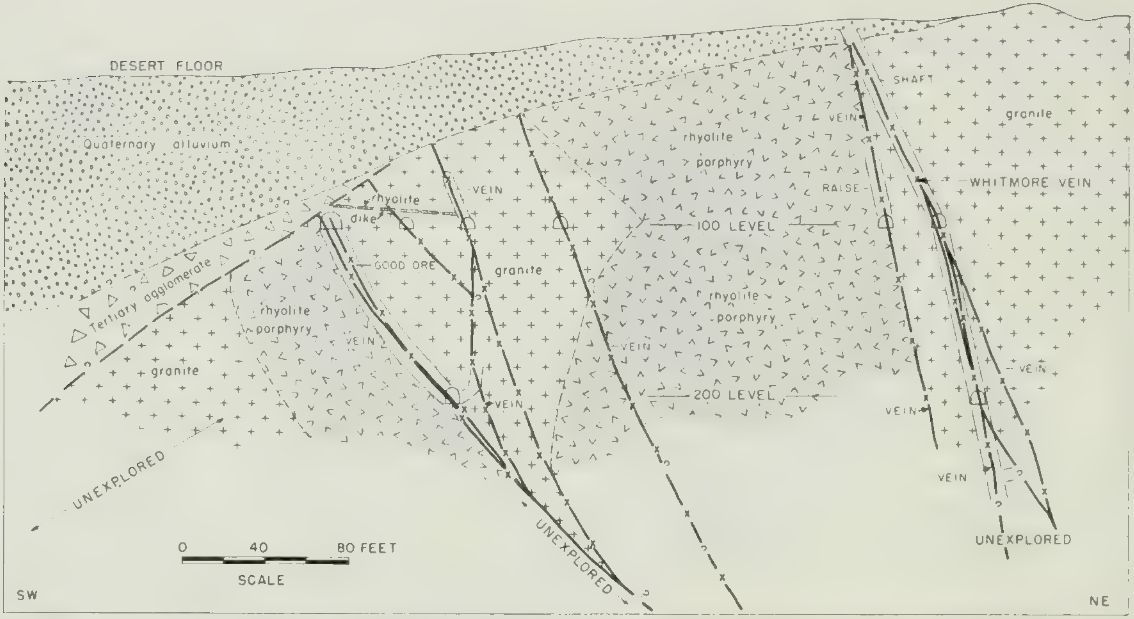

Figure 3. Cross sections of the Whitmore mine, Mojave district, Kern County, California.

secondary enrichment in silver and gold, but development of the mine is as yet too incomplete to settle the question. A coarse-grained rhyolite porphyry is prominent in the mine workings.

Tropico Hill. The Tropico mine is near Rosamond in Kern County. The geology of the mine area is shown in the isometric diagram of plate 3. The principal rock, a rhyolite of late Tertiary (?) age, is broken by a complex fault system. The main Tropico vein is about 5,000 feet in proved length, strikes eastward, and has an average dip of 60° to the south. Ore has been mined from five well-defined shoots in a 1,200-foot segment of the vein. These rake to the west. Oblique faulting is complex, and is both pre- and post-ore in age. The post-ore offsets are small. Horsetail fractures, veins, and "shingle echelons" are found.

The wall rocks are rhyolite (most favorable for ore), intrusive breccia, granite, and agglomerate (unfavorable for ore), and porphyry in the form of dikes and irregular intrusive bodies (unfavorable for ore). Several stages of gold-bearing quartz are present in the altered wall rocks; in general the early material is dense, and the later is drusy. The gold is about 800 fine, but no silver minerals have been identified. Traces of manganese carbonate and its oxidation products also occur, and pyrite is locally present. Spectrographic analyses of some ore samples indicate that a slight increase in lead content is indicative of higher values in gold, but no lead mineral has been identified.

A comparison of wall rocks, ore, and waste indicates a strong chemical similarity between wall rock and vein material. The only significant difference is the presence in the veins of quartz, gold, silver, lead, manganese (?), and traces of minor elements. The latest stage of alteration is represented by strong kaolinization of rhyolite and introduction or transfer to higher elevations of a dark red iron-bearing material, possibly a mixture of jarosite and goethite. Locally this material contains coarse gold and, here and there, silica. No alunite has been recognized on Tropico Hill. Apparently mineralization was completed before this late stage, so evident at the Winkler mine 15 miles to the northwest, was reached at Tropico.

Table 1. Minerals of the Mojave, Randsburg, and Calico districts.

	Mojave district		Randsburg district		Calico district		Mojave district		Randsburg district		Calico district
	Cactus mine	Mojave and Tropico mines	Kelly mine	Gold mines	Various mines		Cactus mine	Mojave and Tropico mines	Kelly mine	Gold mines	Various mines
Metallic minerals						Nonmetallic minerals					
Pyrite	x	x	x	x		Quartz (many stages)	x	x	x	x	x
Marcasite	x		x			Calcite		x	x	x	
Sphalerite	x	x		x	x	Barite	x				x
Galena	x			x	x	Rutile	x				
Tetrahedrite	x		x			Zircon	x				
Pyrargyrite	x		x			Fluorite			x		
Proustite	x		x			Scheelite				x	
Native silver	x	x	x			Allophane			x		
Electrum	x	x	x			Mariposite			x		
Gold	x	x	x	x	x	Gypsum			x		
Stromeyrite	x										
Covellite	x										
Chalcocite	x										
Magnetite	x		x								
Argentite	x	x	x		x	Secondary minerals					
Cinnabar	x					Iron oxides	x	x	x	x	x
Native mercury	x					Chrysocolla		x			x?
Chalcopyrite		x	x		x	Pyrolusite		x			x
Arsenopyrite			x	x		Embolite	x?				x
Stylotypite (?)			x?			Jarosite	x		x?		
Miargyrite			x			Plumbo-jarosite	x				x
Argentiferous bornite (?)			x			Argento-jarosite	x		x?		x?
Stibnite			x			Limonite	x	x	x	x	x
Cerargyrite	x		x		x	Melanterite			x		
Embolite (?)					x	Gypsum			x		

Calico District. Silver was discovered in the Calico district in 1881. Rapid exploration followed until 1896, when the reduced price of silver and the exhaustion of high-grade ore bodies caused production to slump. Mining activity has been slight since 1896, and has become more and more sporadic. No mines are now active.

The productive area of the Calico district is a northwestward-trending belt about 5 miles long and half a mile to 2 miles wide. The richest mines were confined to an area extending from about 1 mile northwest of Calico townsite to about 2 miles east of it.

The silver mines of the district have been developed in and along veins, fissures, and irregular replacement bodies that are associated with shallow plugs of andesite and dacite. The plugs discordantly intrude a thick section of folded and faulted sedimentary and pyroclastic rocks of Miocene age, and are themselves faulted.

The silver mineralization is most extensively developed in some of the intrusive bodies, especially in their peripheral parts, and in the adjacent wall rocks. The distribution of the ore is controlled in part by minor normal faults, where such faults cut the intrusive rocks. Mineralization in the wall rocks is controlled by beds of certain lithology, by their position with respect to the intrusive masses, and to a minor extent by small faults.

MINERALOGY AND ORES

During the course of many years, considerable microscopic work has been done on the ores of the various mines and districts. The minerals that have been determined at some of the mines are listed in table 1 (above). Data for the Kelly mine were obtained largely from Hulin (1925), J. M. Holloway (unpublished report), and R. M. Dreyer (unpublished report). The minerals of the Cactus mine were determined by H. J. Fraser (unpublished report) and Alexander Smith (unpublished report).

As might be expected from the preceding discussions, the ores are extremely variable. Some deposits contain gold or silver that impregnate slightly altered country rock, such as gneiss, schist, granite, or rhyolite, and are unaccompanied by other metallic or nonmetallic minerals. Others are complex sulfide assemblages with abundant quartz, calcite, and alunite. The ores characteristically show intermineral fracturing that indicates a multi-stage history.

With the possible exception of parts of the Mojave district, most of the gold occurrences in southern California are considered to be primary. Rich oxidized ore has its counterparts in unoxidized vein matter. Manganiferous calcite occurs only locally, and, under arid conditions, the migration of gold appears unlikely. Silver, however, is or may be secondary and reconcentrated near the outcrop. It is difficult to account for the larger values at Calico, Silver Hills, and in part of the Kelly mine, except by this hypothesis.

FRACTURE PATTERNS

In most of the districts the earliest faults (subsequently mineralized) are believed to be those that trend northwest and dip steeply to the north. They are possibly related to the Sierra Nevada batholith, and may be marginal fractures along septa of older rocks within the granitic rocks. Steep cross joints, developed at about the same time, trend N. 70° E. to nearly due east. All of these sets of breaks have been reopened, and in some areas major normal faults were developed along parallel trends. Movement on the Garlock and/or San Andreas or parallel faults may have reopened these fractures for invasion by Upper Cretaceous or Tertiary (?) granites, acid volcanic rocks, rhyolite dikes, basic dikes, and mineralizing solutions.

Owing to the dominant horizontal movement on the Garlock fault and the compression that resulted from this movement, folds, thrusts, tear faults, and antithetic (rotational) faults developed in subsidiary blocks. Recurrent movement and mineralization were localized along these pre-existing openings, with development of torsional and linked veins or faults connecting the diverse trends. Some blocks of solid homogeneous granite and other blocks of gneiss and rhyolitic rocks appear to have acted as buttresses around which fractures developed. The resulting pattern of faults and veins is complex; the greater the complexity and the greater the amount of recurrent breaking that has provided channelways for the solutions, the greater has been the likelihood of ore formation. The main faults, however, are generally barren, and the actual junction or intersection areas may also be tight, impermeable, and hence unmineralized.

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7. OCCURRENCE AND USE OF NONMETALLIC COMMODITIES IN SOUTHERN CALIFORNIA

By Lauren A. Wright,[*] Charles W. Chesterman,[**] and
L. A. Norman, Jr.[***]

INTRODUCTION

In view of the wide variety of rock types formed during the course of southern California's eventful geologic history, it is not surprising that deposits within this area (fig. 1) provide all but a small part of an estimated 50 million tons of nonmetallic mineral substances required annually by local industries in recent years. Aggregate and limestone, basic materials of the building and heavy construction industries, are mined in the greatest tonnage. These industries also provide the principal markets for clay, gypsum, and talc, each extensively mined in southern California. Of the numerous other nonmetallic commodities obtained locally, diatomite and salines (see Ver Planck, Contribution No. 1, and Mumford, Contribution No. 2, this chapter) are perhaps the most noteworthy. The salines rank high because southern California is the world's principal source of borate minerals, the principal domestic source of natural sodium carbonate compounds, and is second as a domestic source of potassium salts. Diatomite is significant because more than 70 percent of the world's supply is obtained from unusually large deposits in the upper Miocene marine sedimentary rocks of southern California.

In preparing this summary paper, the authors have attempted to emphasize trends and controlling factors in the technology of nonmetallic commodities in southern California. As illustrative examples, limestone, talc, diatomite, and light-weight aggregate have been given the most attention. For basic data on most of the other non-metals that are commercially significant in southern California the reader is referred to table 1.

The tonnage and value of nonmetallic minerals produced in southern California now far exceeds the output of metallic minerals. This condition is attributable in part to greatly increased demands for non-metals, in part to the near-depletion of many of the metal deposits, and in part to metal prices that commonly are unfavorable in the face of rising mining costs. The producer of nonmetallic minerals, however, is commonly beset by additional problems such as developing and maintaining a market, competition from other producers of similar materials or of other materials used similarly, maintenance of close control in mining and treatment in order to provide a uniform product, and price fluctuations that often are unpredictable.

The development of most nonmetallic mineral deposits is controlled mainly by demand and nearness to market. The basic stimulus to the mining of such deposits in southern California is, of course, the presence of a large and rapidly growing population and the establishment of industries to supply it with housing, utilities, and manufactured commodities. Mineral materials for these industries are ordinarily sought from the nearest adequate supply, and mining operations thus are virtually forced into existence. Operations yielding low-cost, high-tonnage materials that are abundant and widespread, such as low-grade clays, sand, gravel, and crushed rock, cluster within the Los Angeles industrial area. For such operations, however, urbanization is both a reason for and a threat to their existence, as zoning restrictions commonly prohibit their continuance or expansion, thus leading to development of more distant sources of material.

Other commodities of considerable economic importance are not abundant nearby, but are mined in large tonnages within a 250-mile radius of the center of Los Angeles. These include higher-grade ceramic clays, bentonite, diatomite, gypsum, various light-weight aggregates, limestone, pyrophyllite, talc, and specialty sands. For most of these materials, accessibility and transportation costs are prime factors in determining the value of a given deposit. The advantage ordinarily rests with the deposits that are most easily reached, but as they become depleted or incapable of meeting the demand, other, formerly non-economic, deposits can be developed.

Numerous deposits that were considered to be of little or no value a decade or two ago have been brought into production by technological developments. Research in the use of light-weight aggregates, for example, has led to the opening of operations on deposits of expansible shale, pumice, perlite, and volcanic cinders. The development of dust-carried insecticides has provided a market for southern California's pyrophyllite deposits, which were not mined prior to 1942. In recent years a wider variety of rock types has been employed as roofing granules. Investigations of the industrial application of wollastonite may well lead to the development of deposits of this mineral in southern California.

Research also has brought changes in the uses and consequently in the production rates of well established commodities. The use of talc as a ceramic raw material, insignificant in the early 1930's, has increased so much that manufacturers of wall tile and pottery are now the principal talc consumers. The market for feldspar has

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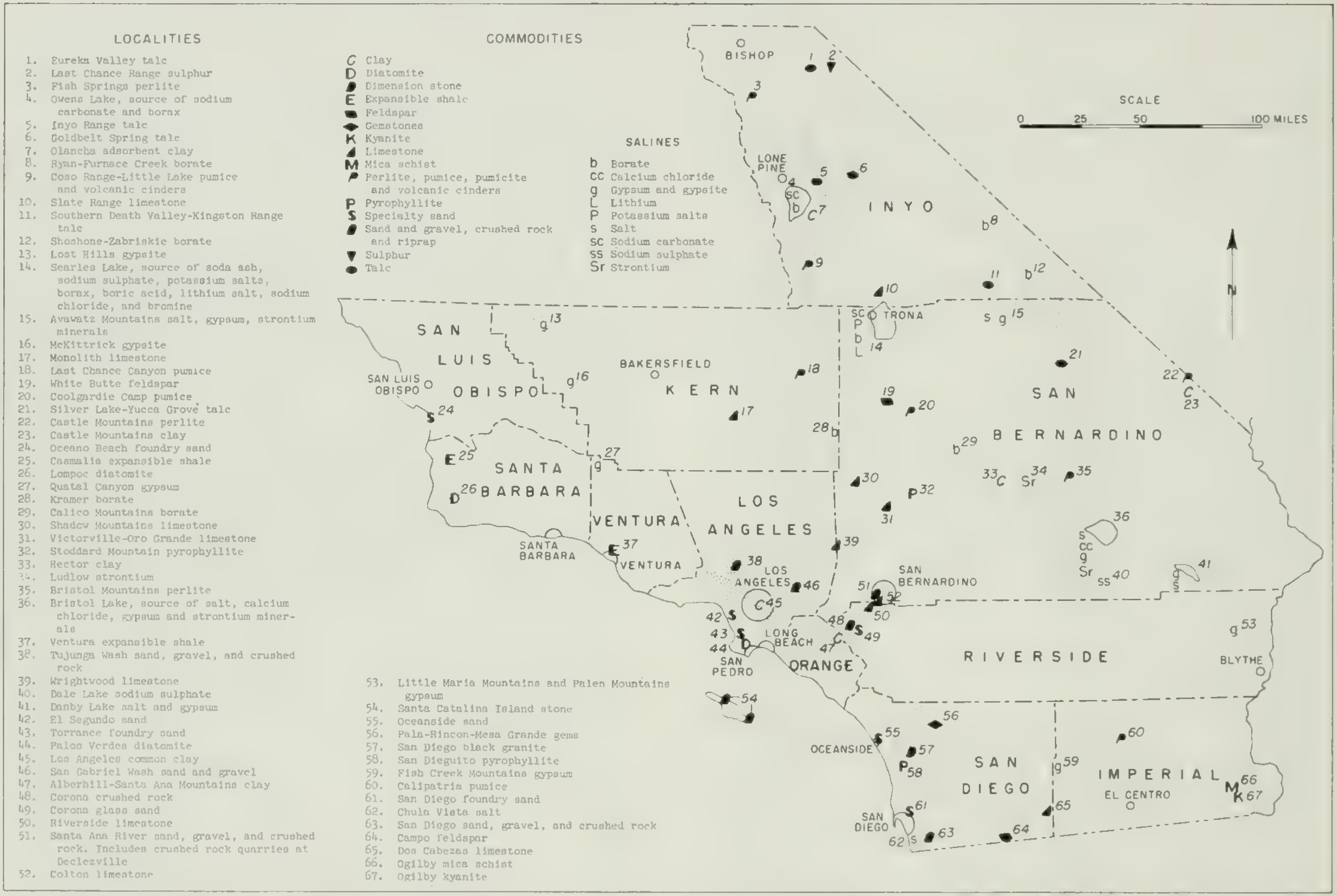
LOCALITIES
1. Eureka Valley talc
2. Last Chance Range sulphur
3. Fish Springs perlite
4. Owens Lake, source of sodium carbonate and borax
5. Inyo Range talc
6. Goldbelt Spring talc
7. Olancha adsorbent clay
8. Ryan-Furnace Creek borate
9. Coso Range-Little Lake pumice and volcanic cinders
10. Slate Range limestone
11. Southern Death Valley-Kingston Range talc
12. Shoshone-Zabriskie borate
13. Lost Hills gypsite
14. Searles Lake, source of soda ash, sodium sulphate, potassium salts, borax, boric acid, lithium salt, sodium chloride, and bromine
15. Avawatz Mountains salt, gypsum, strontium minerals
16. McKittrick gypsite
17. Monolith limestone
18. Last Chance Canyon pumice
19. White Butte feldspar
20. Coolgardie Camp pumice
21. Silver Lake-Yucca Grove talc
22. Castle Mountains perlite
23. Castle Mountains clay
24. Oceano Beach foundry sand
25. Casmalia expansible shale
26. Lompoc diatomite
27. Quatal Canyon gypsum
28. Kramer borate
29. Calico Mountains borate
30. Shadow Mountains limestone
31. Victorville-Oro Grande limestone
32. Stoddard Mountain pyrophyllite
33. Hector clay
34. Ludlow strontium
35. Bristol Mountains perlite
36. Bristol Lake, source of salt, calcium chloride, gypsum and strontium minerals
37. Ventura expansible shale
38. Tujunga Wash sand, gravel, and crushed rock
39. Wrightwood limestone
40. Dale Lake sodium sulphate
41. Danby Lake salt and gypsum
42. El Segundo sand
43. Torrance foundry sand
44. Palos Verdes diatomite
45. Los Angeles common clay
46. San Gabriel Wash sand and gravel
47. Alberhill-Santa Ana Mountains clay
48. Corona crushed rock
49. Corona glass sand
50. Riverside limestone
51. Santa Ana River sand, gravel, and crushed rock. Includes crushed rock quarries at Declezville
52. Colton limestone
53. Little Maria Mountains and Palen Mountains gypsum
54. Santa Catalina Island stone
55. Oceanside sand
56. Pala-Rincon-Mesa Grande gems
57. San Diego black granite
58. San Dieguito pyrophyllite
59. Fish Creek Mountains gypsum
60. Calipatria pumice
61. San Diego foundry sand
62. Chula Vista salt
63. San Diego sand, gravel, and crushed rock
64. Campo feldspar
65. Dos Cabezas limestone
66. Ogilby mica schist
67. Ogilby kyanite
COMMODITIES
C Clay
D Diatomite
Dimension stone
E Expansible shale
Feldspar
◆ Gemstones
K Kyanite
▲ Limestone
M Mica schist
Perlite, pumice, pumicite and volcanic cinders
P Pyrophyllite
S Specialty sand
Sand and gravel, crushed rock and riprap
▼ Sulphur
● Talc
SALINES
b Borate
CC Calcium chloride
g Gypsum and gypsite
L Lithium
P Potassium salts
s Salt
SC Sodium carbonate
SS Sodium sulphate
Sr Strontium
SCALE
0 25 50 100 MILES
N
BISHOP
LONE PINE
INYO
TRONA
SAN LUIS OBISPO
KERN
BAKERSFIELD
SAN BERNARDINO
SANTA BARBARA
VENTURA
LOS ANGELES
SAN BERNARDINO
LONG BEACH
SAN PEDRO
ORANGE
RIVERSIDE
BLYTHE
OCEANSIDE
SAN DIEGO
IMPERIAL
EL CENTRO

FIGURE 1. Index map of southern California showing locations of nonmetallic mineral resources. Stippled areas contain numerous deposits of the indicated commodity.

been restricted correspondingly. The development of synthetically prepared foundry sands has increased the demand for high-silica sand and refractory clays, and has decreased the demand for the so-called naturally bonded sands. The introduction of sand-blasting techniques has increased the output of specialty sands in California by about 100,000 tons a year.

Some other operations yield products that are valuable enough or scarce enough elsewhere to permit their distribution well beyond the limits of southern California. Boron products and diatomite are shipped the world over. Much of the potash, soda ash, lithium salts, and talc produced in southern California is shipped to other states and even to other countries.

Nonmetallic materials also are obtained as by-products from other types of operations. For example, a small but significant fraction of the sulfur consumed in southern California is recovered from waste gases of petroleum refineries. All of the iodine currently produced in the United States is obtained from brines pumped by producing oil wells in the Los Angeles basin.

The southern California area is particularly deficient in deposits of asbestos, high-grade silica sand, sulfur, swelling bentonite, and china clay. Although about 200,000 tons of silica sand is annually brought in from out-of-state sources, the added cost of this transportation permits the profitable beneficiation of a lower-grade sand deposit near Corona, Riverside County. This deposit, which the casual observer would expect to be of little commercial value, supplies about half of the material used in southern California glass plants. The scarcity of local deposits of china clay similarly permits the profitable extraction of this material by the treatment of clay-rich sandstone mined in the Santa Ana Mountains. Increases in freight rates are commonly cited as encouraging the beneficiation of local materials. Other observers minimize the effect of such increases, and aver that they represent an inflationary trend that is reflected in increased costs of beneficiation.

Not to be overlooked in a discussion of the controlling factors of nonmetallic mineral production is the personal element. Even more so than in most businesses, the success of an operation is likely to depend largely upon the judgment, imagination, and energy of an individual. This is particularly evident in many of the smaller mines and quarries, yielding from a few tons to a few hundred tons daily, and which require only a modest capital investment. Deposits of clay, gypsite, talc, pyrophyllite, specialty sands, roofing-granule materials, and dimension and ornamental stone are among those being successfully developed by small-scale operations.

The non-metal field is thus subject to numerous and variable influences apart from the quality and quantity of material available, especially demand, accessibility of deposits, transportation costs, changes in usage, development of beneficiation techniques, and the personal factor. These influences are in a state of constant adjustment, and the problems they raise challenge the mineral economist and industrial consumer as well as the geologist and mining engineer. The field has become so wide that virtually every rock unit in southern California could well be thought of in terms of its potential use as a nonmetallic mineral commodity; this is a consideration that often is disregarded in geological studies.

LIMESTONE

Limestone, used principally in the manufacture of portland cement, is mined and consumed in southern California at the rate of about 5,000,000 tons a year. It also is marketed as an agricultural mineral, a filler, a roofing-granule material, whiting, and as a metallurgical flux. In addition it is employed in the manufacture of quicklime and hydrated lime for use in numerous industrial applications.

The cement manufacturers in southern California, as elsewhere, operate captive deposits of limestone. A high-tonnage and low-cost commodity, the limestone must be mined and brought to the plant cheaply, ordinarily at a cost in the range of 25 to 50 cents per ton as contrasted with a much higher price for the cement obtained from it. The plants are therefore located near raw-material sources as well as near a railroad. In general, the cement companies in southern California have been faced with the operation of deposits more complex in lithology and structure, and farther from the principal markets than the deposits of most cement-producing centers.

The limestone resources of greatest commercial significance to the Los Angeles metropolitan area are centered about the Mojave Desert region, where thick carbonate units of Paleozoic age are extensively exposed. Few limestone deposits exist in the Peninsular, Transverse, and Southern Coast Ranges, which are composed mostly of Mesozoic and Cenozoic sedimentary rocks, plutonic units of the southern California batholith, and pre-batholith metavolcanic and metasedimentary rocks. The principal exceptions are the limestone deposits of the Colton-Riverside area, which lie just within a 50-mile radius of the center of Los Angeles. These deposits supply two large cement plants, one at Slover Mountain near Colton, San Bernardino County (fig. 2), and another at Crestmore, Riverside County. Active deposits in the Mojave Desert region, which are two to three times farther away, supply three additional plants, one each at Victorville and Oro Grande, San Bernardino County, and the other at Monolith, Kern County.

The two plants nearest Los Angeles were the first to be put in operation as major local sources of portland cement, the Colton plant

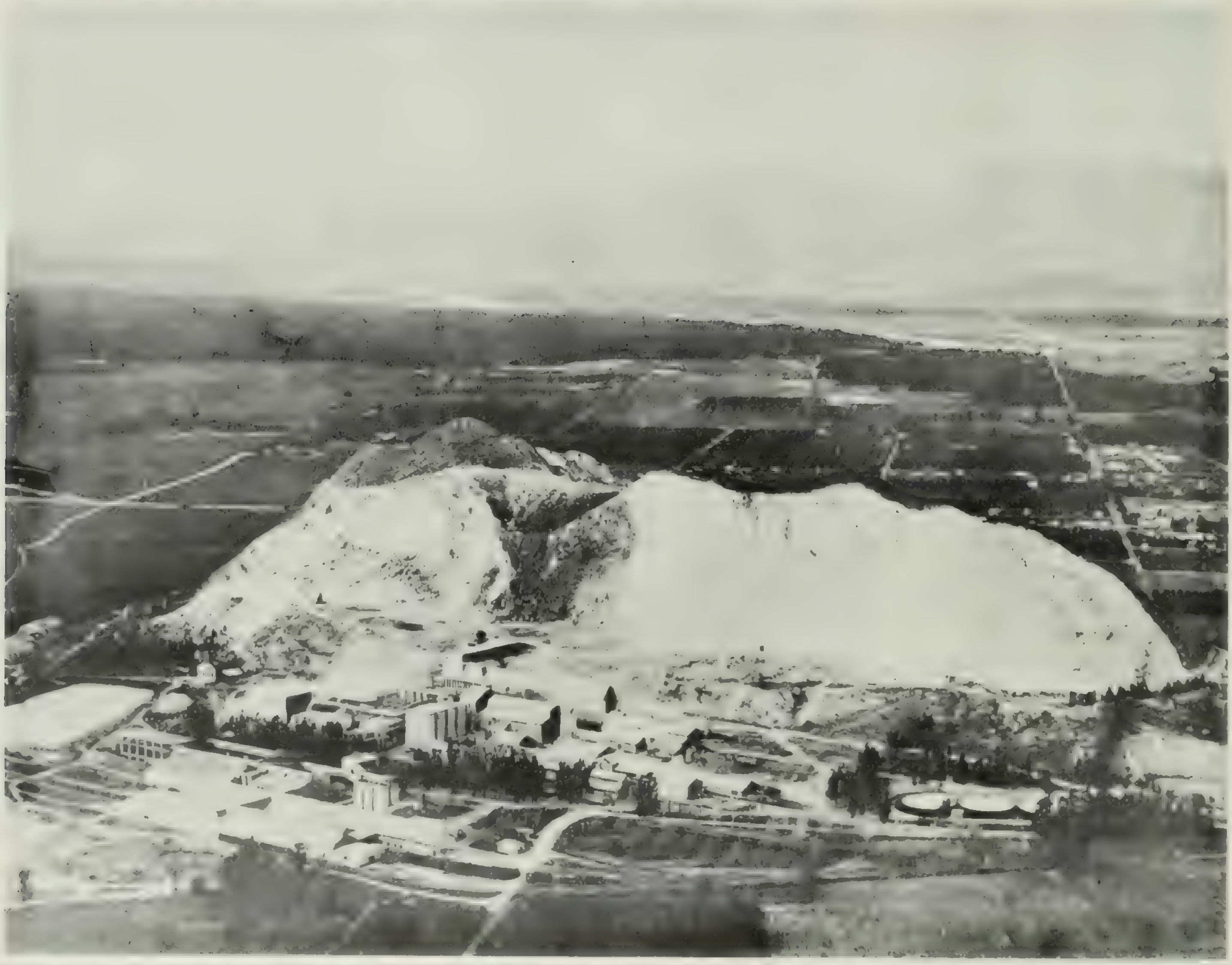

FIGURE 2. View eastward of quarry and plant of Southwestern Portland Cement Company, Colton, San Bernardino County. *Photo courtesy Southwestern Portland Cement Company.*

in 1894 by the California Portland Cement Company, and the Crestmore plant in 1909 by the Riverside Cement Company. Also in 1909 the plant at Monolith was constructed by the City of Los Angeles to provide cement for the construction of the Owens River aqueduct. Not until 1921, when the plant was acquired by the Monolith Portland Cement Company, was its output shipped into the Los Angeles area. In the meantime the development of the Oro Grande area had begun in 1910 with the opening of the Golden State Portland Cement Company plant, and in 1916 the plant of the Southwestern Portland Cement Company was established at Victorville. In 1923 the Oro Grande plant was acquired by the Riverside Cement Company. It was idle from 1928 to 1942, but has since been modernized and enlarged.

These five plants, with a combined rated capacity of about 16,000,000 barrels per year, now supply virtually all of the cement requirements of southern California, as well as parts of Nevada and Arizona. During periods of temporary shortage in southern California, cement is brought in from plants in the northern part of the state and from others as far distant as Colorado. When needed, cement also is shipped from southern to northern California.

Although unworked limestone deposits are present at numerous localities throughout the desert regions of southern California, their development has been prevented or delayed by their greater distances from market areas or by their more difficult accessibility. As the nearer sources become depleted or too costly to mine, deposits farther from the plants are being developed. Open-pit mining methods generally are employed, although the Crestmore deposits have been worked underground for many years.

The limestone in the deposits worked to date is ordinarily medium to coarse grained, and is commonly interlayered with quartzite and mica schist. Minable deposits range in thickness from a few tens of feet to several hundred feet, and are as much as a mile in length. Some of the inactive deposits at greater distances from Los Angeles are much larger.

Limestone mined in the Victorville-Oro Grande area occurs in the Carboriferous Ore Grande series and Permian Fairview Valley formation (see McCulloh, Contribution No. 2, chapter VII, and Bowen, Map Sheet 18). The Crestmore (see Burnham, Contribution No. 7, chapter VII) and Colton deposits have yielded no fossils, but have been tentatively correlated with either the Triassic Bedford Canyon formation of the Santa Ana Mountains (MacKevett, 1951, pp. 4-5) or the Upper Paleozoic limestones that crop out on the north slope of the San Bernardino Mountains (Woodford, 1943, p. 336). The Monolith deposits are a part of the Kernville series, and probably are Paleozoic in age (T. W. Dibblee, Jr., personal communication).

Nearly all of the mined deposits are parts of roof pendants in granitic rocks, and are involved in very complex structures. Many of the deposits contain numerous smaller bodies of intrusive rocks, which generally contribute objectionable impurities if they are not discarded in mining. Most harmful are the alkalies of the felsic bodies and the magnesium of the mafic bodies. Some intrusive rocks of intermediate composition, however, commonly can be ground with the limestone and supply desirable aluminous material to the cement.

Dolomite, common as layered or irregular masses in many of the limestone deposits, also is a source of magnesium impurity, and must be avoided in mining. Deposits that contain dolomite ordinarily are drilled before they are mined, and close control of the materials is established by chemical analyses during both exploration and production. Removal of dolomite by benefication may prove to be practical at some future time.

Limestone, if mined for uses other than as a cement ingredient, commonly is held to specifications that are predominantly physical rather than chemical. Some operations are sustained on deposits whose color, crushing properties, or strength make the material desirable for such uses as filters, roofing granules, and whiting.

TALC

High-quality commercial talc, commonly a mixture of magnesium silicate minerals rather than the pure mineral talc, is one of the nonmetallic commodities whose restricted occurrence and many uses permit it to be mined even at considerable expense, and to be transported hundreds or even thousands of miles for milling and marketing. Such talc ordinarily is valued in the range of 7 to 15 dollars per ton at the mine, and at three or four times as much when ground and bagged.

Talc mined in southern California is used mostly as a ceramic raw material, as a paint extender, and as sizing in textiles. These and numerous other industrial uses stem largely and variously from its soft nature, chemical inertness, whiteness, and desirable firing properties.

Most of the 100,000 tons of talc now mined in the State each year is obtained from a narrow belt that extends south-southeastward for a distance of about 200 miles from the Bishop area in Inyo County to the vicinity of Baker in San Bernardino County. This belt is divisible into three talc-bearing districts, one embracing the Inyo Mountains and part of the northern Panamint Range, another extending from southern Death Valley eastward to the Kingston Range, and the third including the Silver Lake and Yucca Grove areas near Baker. Each district differs from the others in its geologic features, and particularly in the type and apparent origin of its talc deposits.

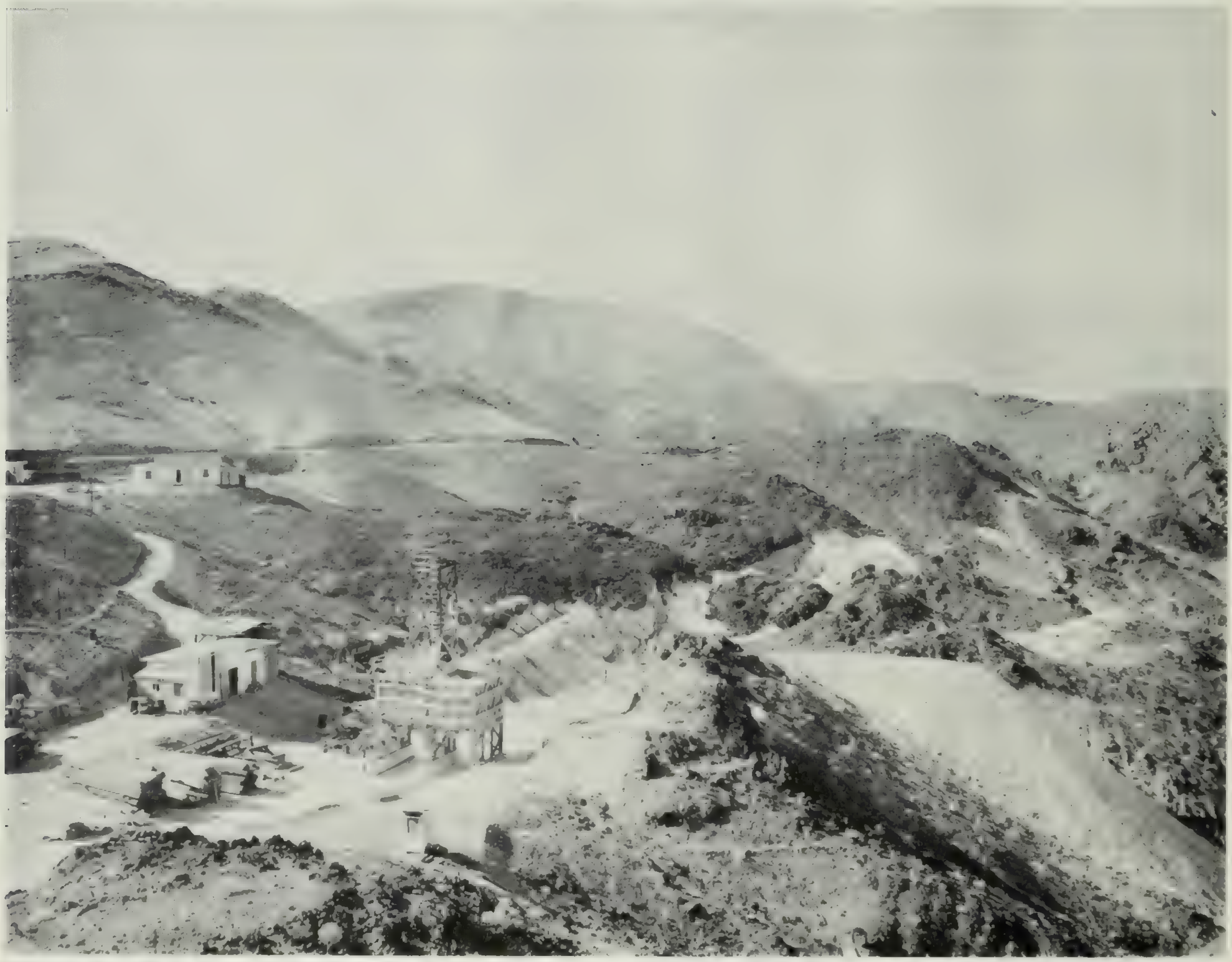

FIGURE 3. View of Superior talc mine, San Bernardino County, looking southwestward. Talc deposit (white) dips moderately southeastward beneath diabase sill that underlies most of hill on left. Deposit is underlain by quartzite and shale. All units are part of Algonkian Crystal Spring formation.

Most, if not all, of the talc deposits of the Inyo Mountains and northern Panamint Range are associated with Ordovician and Silurian sedimentary rocks. The talc has been formed largely by alteration of dolomite in the Pogonip (Lower Ordovician) and Ely Springs (Upper Ordovician) formations and in Silurian units. Other deposits are wholly or in part alterations of the Eureka quartzite (Middle Ordovician) and of Silurian quartzite. Talc in commercial quantities has been formed locally by alteration of Mesozoic granitic rocks.

The individual bodies of talc are lenticular to very irregular, and the largest are several hundred feet long. Most appear to have been formed along zones of fracturing or shearing, and commonly lie at or near major lithologic contacts, especially contacts between dolomite and quartzite. Unlike many commercial talcs, the material composing these bodies approaches the pure mineral in chemical composition, and generally is free of the tremolite that is so common in deposits of the other two districts. The deposits are of low-temperature, hydrothermal origin, and show no apparent genetic relationship to exposed intrusive bodies. Most or all of the additive MgO appears to have been derived from nearby dolomite.

The principal talc deposits of the southern Death Valley-Kingston Range area lie at or near the base of a massive carbonate member in the Algonkian Crystal Spring formation, and also are at or near the margins of an extensive Algonkian diabase sill (fig. 3). They have been formed by the silication of carbonate strata, ordinarily dolomite or siliceous dolomite. Although the silication commonly has been too weak to yield material of commercial interest, several active mines have been developed in deposits that range in length from 1,000 feet to a mile or more, and that are 20 to 25 feet in average thickness. The silicated zones are mainly mixtures of talc, tremolite, serpentine, and calcite. Either talc or tremolite greatly predominates in most of the commercial rock. These deposits were formed by the addition of MgO and commonly of SiO_2, evidently without loss in volume. The added material appears to have been derived from the cooling diabase, but at least part of the MgO might have been drawn from ground-water if the sediments were poorly consolidated at the time of diabase intrusion.

The talc deposits near Silver Lake and Yucca Grove appear to have been formed by the selective and nearly complete silication of certain carbonate layers in a section of sedimentary rocks that are much more highly metamorphosed than the Paleozoic and Algonkian rocks noted above, and consequently have been tentatively dated as older pre-Cambrian (Wright, 1954). These metasedimentary units have been extensively invaded by bodies of granitic rock and locally by earlier bodies of mafic rock.

The principal talc-bearing belt, 9 miles northeast of the Silver Lake playa, is 2 miles long and contains several workings known collectively as the Silver Lake mine. Here individual talc bodies, a few as much as 800 feet in proved length, lie near the center of a hornfels member of the metasedimentary section. Most of the commercial bodies are 10 to 15 feet thick, and they ordinarily occur as parts of two parallel layers separated by hornfels.

The deposits comprise two general rock types: massive tremolite rock and talc schist. Forsterite and serpentine are abundant in some of the tremolite rock. Most of the silication probably was contemporaneous with the emplacement of the larger bodies of granitic rock, and followed a period of higher-temperature metamorphism in which the forsterite was formed, probably in silica-poor dolomite. The talc schist has been developed in the tremolite rock, apparently along zones of stress and under conditions of still lower temperature. Additive MgO and SiO_2 may have been derived from a granitic magma, and MgO also may have been transferred during the granitization of magnesium-rich sedimentary rocks.

About 60 talc mines have been worked at one time or another in eastern California. All but a small part of the total output has been contributed by 14 operations: the Talc City, Bonham (White Mountain), Alliance, and Nicolaus mines in the Inyo Mountains area; the Western, Superior (fig. 3), Warm Spring, Monarch, Ibex, and Smith mines in the southern Death Valley-Kingston Range area; and the Silver Lake, Pomona, and Calmasil mines in the Silver Lake-Yucca Grove area. At typical mines moderately steep talc bodies are followed by means of shafts, drifts, and winzes, and the talc is removed from overhand stopes. None of the workings as yet extends more than 500 feet in a down-dip direction. Some of the deposits require much timbering, and others almost none. Most of the talc is ground at mills in the Los Angeles area, some is ground at mills near the deposits, and the remainder is shipped to mills as far distant as Grand Island, Nebraska. Talcs from two or more deposits commonly are blended to assure uniformity.

LIGHT-WEIGHT AGGREGATES

General Features. The use of light-weight materials as aggregate in concrete and plaster has become widespread during the past two decades. By 1940, the consumption of such materials in southern California increased from a negligible figure to about 300,000 tons annually, and led to the opening of numerous deposits that previously had been of little or no commercial value.

Pumice, in the past employed mainly as an abrasive, is now widely used as an aggregate in plaster, building blocks, and in monolithic concretes. Perlite, of little commercial interest prior to 1945, has been used in expanded form mainly in acoustical and fireproofing plasters and in insulating concretes. Expanded shale, although used in California during the mid-1930's as aggregate in the deckings of the Golden Gate and San Francisco Bay bridges, was introduced commercially in southern California about 1947. It is employed primarily in the manufacture of building blocks, slabs, and monolithic concretes.

Volcanic cinders (scoria), whose principal use prior to the mid-1940's was as railroad ballast, is now mined in southern California as an aggregate in building block and concrete. Such concrete has higher specific strength than those made with most other light-weight materials. Vermiculite, though not mined in the State, has been used as aggregate in plaster and concrete in southern California for many years. It is shipped in from out-of-state sources.

In 1952 about 120,000 tons of pumice, 80,000 tons of expanded perlite, 80,000 tons of expanded shale, and several thousand tons of volcanic cinders were consumed as aggregate materials in southern California. All of these materials compete directly with sand and gravel, which are obtained from sources much nearer the Los Angeles industrial area and ordinarily are mined less expensively. Because of their low cost and high strength, sand and gravel should continue as the "backbone" of the aggregate industry.

Sand and gravel are marketed in southern California for about $1.00 per ton, whereas the market value of pumice, expanded shale, expanded perlite, and volcanic cinders ranges from $15.00 to $80.00 per ton. In spite of higher prices that are only partly offset by the greater volume per ton, the market for light-weight aggregates has developed rapidly and continues to grow because of increased demands by the building industries for construction materials that have (1) low bulk densities, and (2) good insulating and fireproofing properties.

Ordinary sand and gravel weigh 100 pounds or more per cubic foot, whereas pumice, expanded perlite, expanded shale, and volcanic cinders weigh from 7 pounds to 50 pounds per cubic foot.

In general, each of the light-weight aggregate materials has a definite field of effective usefulness that overlaps, to some extent, the fields of the others. Pumice, volcanic cinders, and expanded shale, for example, each make moderate- to high-strength concretes, whereas expanded perlite, vermiculite, and some pumice are used in insulating and acoustical plasters.

The sources of these light-weight aggregate materials lie well outside the Los Angeles industrial area, and are concentrated in the desert regions of eastern and southern California, where volcanic formations are extensively exposed. Expansible shale is mined at two southern California localities, one in Ventura County and another in Santa Barbara County. Perlite also is obtained from deposits in Nevada and New Mexico, and vermiculite is brought in from Montana, Colorado, and Idaho.

Perlite: General Features. Nearly all of the perlite rock treated in expansion plants in southern California was shipped from deposits in Arizona and Nevada until 1948, when production began from deposits near Fish Springs, Inyo County, and deposits in the Bristol Mountains northeast of Ludlow, San Bernardino County. Although many other large deposits are present in eastern and southern California, these two were the first to be developed because they contain large tonnages of easily minable, expansible perlite that are close to good rail and highway transportation and relatively close to the principal markets.

In a commercial sense the term "perlite" is applied to any glassy volcanic rock that will expand upon heating. In almost all of its occurrences the rock is either late Tertiary or Recent in age. Most perlites are acidic in composition, and ordinarily are associated with rhyolite and tuff. Bodies of perlite occur in flows, sills, dikes, and plugs or domes. Perlite also occurs locally as irregular bodies in larger masses of rhyolite, or as selvages in dikes or sills of rhyolite, dacite, or andesite.

The bodies show a wide range in size, and the perlite shows a wide range of physical characteristics. Very few known perlite bodies in southern California contain more than a million tons of expansible material, and most of them probably contain no more than several tens of thousands of tons. The perlite itself ranges in color from black through shades of dark and light gray to mottled brown and gray. Most has either an "onion-skin" or a granular texture. The granular type probably is the more desirable, as it grinds uniformly and expands well.

At Fish Springs, in Inyo County, the perlite occurs in a complex volcanic dome, which forms a conspicuous hill about 200 feet high near the base of the Sierra Nevada. The dome is capped by pumiceous perlite that grades downward into less pumiceous perlite. The entire perlite zone is about 80 feet thick, and is underlain successively by brecciated obsidian in a pumiceous perlite matrix, and by a dense, glassy, perlite vitrophyre.

In the Bristol Mountains, northeast of Ludlow, the perlite occurs in gently dipping flows of various thicknesses. These are interbedded with tuffs, tuffaceous sediments, and rhyolite flows. The perlite has an onionskin texture, and locally contains irregular bodies and veinlets of chalcedonic and opaline silica.

Genesis of Perlite. Nearly all perlite deposits in southern and eastern California contain minor proportions of obsidian in masses

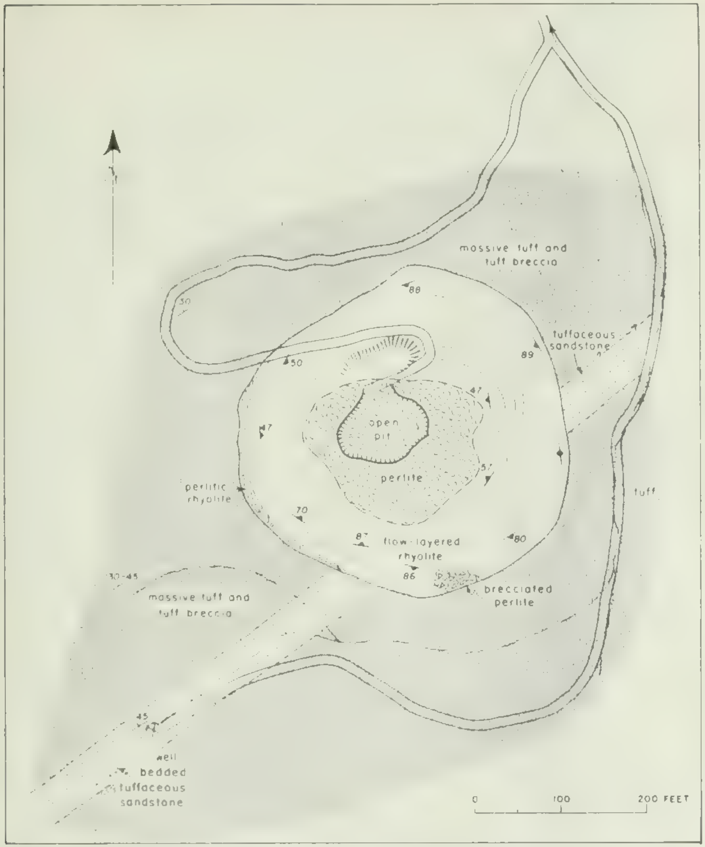

FIGURE 4. Geologic sketch map of the Cedar Top perlite deposit, Castle Mountains, San Bernardino County, California.

that appear to be remnants of an older rock from which the perlite developed. The process of "perlitization" is particularly well shown in the Cedar Top deposit of the Castle Mountains, in eastern San Bernardino County. The perlite at this deposit occupies the central part of a circular plug-dome of rhyolite, about 400 feet in diameter, that has been intruded into a moderately dipping, northeast-trending sequence of rhyolite tuffs, tuff breccias, and tuffaceous sandstone (fig. 4). The rhyolite shows a well-defined flow layering that in general dips steeply inward toward the center of the dome. The perlite, which has well-developed perlitic structure, grades into the rhyolite. Joints cut the perlite, and ordinarily contain a fraction of an inch to several inches of pink montmorillonite which appears to have altered from the perlite.

Scattered throughout the perlite are cavernous, rounded masses of spherulitic rhyolite, ½ inch to 3 feet in diameter, that commonly are bordered by a thin shell of montmorillonite. The perlite also contains numerous irregular bodies and veinlets of opaline silica and aragonite. Obsidian forms only a small part of the deposit. It is jet black, and occurs in rounded bodies that range in diameter from ¼ inch to 1 inch. These are Marekanites, and also are called "Apache tear drops" by the amateur mineralogist. The obsidian apparently is residual glass unconverted to perlite. A typical fragment of obsidian, surrounded by perlite that also fills fractures in the obsidian, is shown in figure 5. Such fragments are everywhere encased by concentric shells of light gray perlite.

The following sequence of events is thought to account for the relations of the Cedar Top deposit: (1) intrusion of the rhyolite-obsidian dome into the tuffaceous rocks, and formation of spherulites in the obsidian, (2) fracturing and brecciation of the obsidian during or following emplacement of the dome, (3) conversion of the obsidian to perlite, the completeness of alteration depending upon the degree of access of water vapor, and (4) deposition of silica along fractures in the perlite, and formation of montmorillonite.

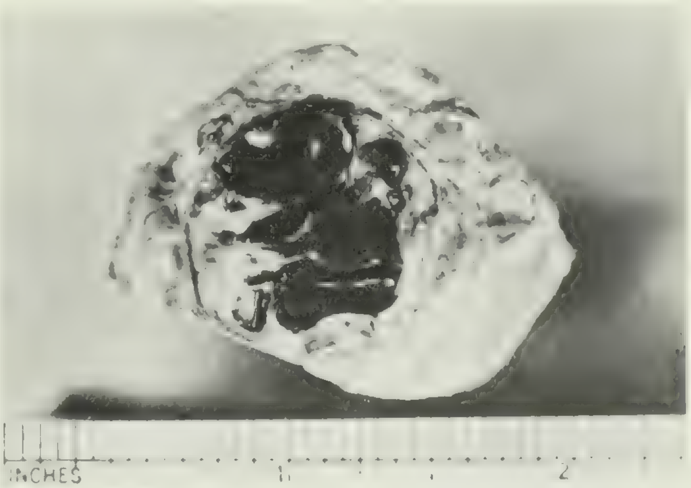

FIGURE 5. Obsidian nodule (black) bordered and veined by perlite (light). Specimen from Cedar Top deposit, Castle Mountains, San Bernardino County.

The temperature during perlitization was below the crystallizing temperature of the glass, estimated at 400° to 500° C. The water probably was derived in part from the intruded rocks and in part from the rhyolite, which may still have been crystallizing. Evidently enough water vapor was available to permit formation of montmorillonite and opaline silica.

Mining and Processing of Perlite. Perlite is mined selectively by fairly simple open-pit methods. After crushing, it is screened very carefully, as the uniformity of the expanded product is dependent wholly upon the accuracy of sizing of the unexpanded material.

Although perlite can be expanded in various types of furnaces, the present trend favors the flash type, in which the sized material is fed directly into the flame. It is ejected seconds later, when, by expanding and thus decreasing in density, it becomes buoyant enough to be carried out by the escaping hot gases. The expanded perlite is removed from the gas stream by means of cyclones and bag houses, and is then packaged.

Pumice. In the early 1930's, deposits in Mono County were the principal sources of the relatively small tonnages of pumice aggregates then used in southern California. Shortly before World War II, however, pumice mining was begun in the southern part of the Coso Range in southern Inyo County, about 100 miles nearer Los Angeles. These two counties now supply most of the pumice aggregate used in southern California. Other deposits are worked in the El Paso Mountains, Kern County, in the Opal Mountain area, San Bernardino County, and in the Calipatria area, Imperial County.

Most pumice aggregate is produced from loosely consolidated, mantle-like tuffs that occur at or near the surface of the ground. A smaller, yet substantial, output is obtained from well-consolidated tuff beds whose overburden may exceed several tens of feet in thickness. The deposits of pumice, like those of perlite, range in age from late Tertiary to Recent. Most of the late Tertiary deposits are in tuffaceous layers that are underlain and overlain by flows of rhyolite, andesite, and even of basalt.

At the deposit in the Opal Mountain area, the pumice is mined from a series of tuffaceus beds, about 90 feet in total thickness, that lie upon deeply eroded Mesozoic granitic rock and are overlain by flows of rhyolite that grade upward into perlite. The pumice deposits in the southern part of the Coso Range probably are late Quaternary in age, and form thick, mantle-like deposits of loosely bonded fragments. These deposits rest upon deeply eroded granitic rocks, and are overlain by a pumiceous soil. Some of the Coso pumice evidently accumulated on dry land, and lacks bedding and is poorly sorted. Some settled in standing water, and is well bedded and contains sandy layers. The deposits in the Calipatria area commonly are admixed with late Quaternary sand and gravel that in part overlap domes of vesiculated obsidian.

The Mono County pumice deposits, some north of Bishop and others near Laws, are late Quaternary in age. Deposits along the southern margin of the Volcanic Tableland, north of Bishop, are overlain in part by the Bishop tuff (Gilbert, 1938, pp. 1829-1862), a welded rhyolite tuff. The pumice near Laws is associated with fanglomerates that are exposed low on the west flank of the White Mountains. Here pumice fragments form discontinuous beds 20 to 30 feet thick.

The minable reserves of aggregate pumice in the desert regions of California are large, and are estimated to be of the order of 5,000,000 tons or more. At the current rate of consumption, about 100,000 tons annually, these deposits can be worked for many more years.

Nearly all pumice for aggregate purposes is mined by open-pit methods. In general, the overburden must be no more than 20 feet thick. Clay and small fragments of stone are troublesome, but large boulders are easily removed by coarse screening. The smaller fragments of pumice are screened, and are marketed in various sizes.

Volcanic Cinders (Scoria). Quaternary cinder cones are conspicuous in many parts of the desert regions of southern California, and they contain very large reserves of material suitable as light-weight aggregate. Three of the more accessible cones, one at Little Lake in Inyo County, and the others at Mt. Pisgah and Dish Hill in San Bernardino County, have yielded such material in commercial amounts.

The cones range in height from 300 to 500 feet. The cinders generally are basaltic in composition, brick-red to black in color, and consist of particles that range in size from a fraction of an inch to several inches. Volcanic bombs ordinarily are mixed with the cinders. The material is mined by means of scrapers and bulldozers, and is screened to coarse and fine aggregate. Coarse aggregate, minus 1-inch and plus $\frac{1}{16}$-inch material, is used mostly in building blocks and concrete. The minus $\frac{1}{16}$-inch material, or fines, is used in plaster and stuccos.

Expanded Shale and Burned Shale. Expanded shale and burned shale are aggregates that only recently have become established commercially in southern California. Shales composed of illitic clays appear to make the best expanded aggregate. Although very little is yet known of the extent and characteristics of the expansible-shale deposits in the State, they probably are abundant and widespread.

Almost all of the expanded shale consumed in southern California is obtained from a deposit at Ventura in Ventura County. This operation is in the Mudpit shale (Plio-Pleistocene). An oil-impregnated diatomaceous mudstone that occurs in the Sisquoc formation (Mio-Pliocene) is mined near Casmalia in Santa Barbara County, and is burned to produce a light-weight material.

The shale and mudstone at the two operations are mined in open pits by means of scrapers and bulldozers. At Ventura the shale is crushed and sized, and then is expanded in rotary kilns. The product is used as aggregate in making building blocks and slabs. At the Casmalia operation, the oil-impregnated mudstone is stacked in long parallel piles, which are set afire and allowed to burn until all oil has been consumed. The burned or sintered mudstone is then crushed and screened, and is marketed either as aggregate or as pozzolan. The expansion at the Ventura operation probably is caused by volatilization of water and natural hydrocarbons. The low density of the Casmalia material is an effect of its diatomaceous character and the loss of its oil content.

Vermiculite. Exfoliated vermiculite has been used for many years in southern California, both as plaster and concrete aggregate and as loose-fill insulation. Although no vermiculite has been produced in the State for these purposes, small amounts are being mined in San Diego County for use in conditioning soils. At least six exfoliating plants in southern California process unexpanded vermiculite obtained from sources in Montana, Idaho, and Colorado.

DIATOMITE

The diatomite deposits of southern California are noted for their purity and size. They constitute the most significant, if not the largest, resources of commercial diatomite in the world, and they supply about 75 percent of the world's requirements, including most of the 300,000 tons consumed annually in the United States. Most of the diatomite mined in southern California is valued at the plants in the range of $40 to $150 per ton, and hence commands prices that make possible the relatively expensive mining and processing methods required to provide uniform products.

Diatomite is a light-weight sedimentary rock that is composed largely of the shells of minute silica-secreting plants called diatoms. These plants were particularly abundant in the sea that covered parts of California during late Miocene and early Pliocene time, perhaps because the water was unusually rich in dissolved silica, derived from submarine volcanism, that the diatoms could utilize. In some places the diatom shells accumulated in extensive beds with very little other material. These beds are interlayered with diatomaceous siltstone, and commonly form from several hundred to several thousand feet of the upper Miocene-lower Pliocene section. Most of the diatomite mined to date has been obtained from upper Miocene strata in the Lompoc area of Santa Barbara County, and in the Palos Verdes Hills of Los Angeles County.

More than 300 uses have been developed for diatomite, but the largest tonnages are employed in the filtration of sugar syrups, wine, beer, pharmaceuticals, drinking water, food products, dry-cleaning solvents, petroleum products, and many other materials. Diatomite also is used as a filler in such products as paint, varnish, paper, plastics, matches, and insecticides; as an anti-caking agent in ammonium nitrate fertilizers; as an insulating material; as a constituent of concrete; as a catalyst carrier; as an abrasive in metal polishes; and as an ingredient of water absorbents. In 1950, about 57 percent of the domestic consumption of diatomite was employed in filteraids, 28 percent in fillers, 8 percent in insulation, and 7 percent in various other uses. Consumption in southern California is probably in the range of 15,000 to 20,000 tons per year.

The usefulness of diatomite stems from the unusual physical structure of the diatom shells, and from their siliceous composition and chemical inertness. The shells are microscopic, hollow forms that occur in many shapes, most common among which are disks and needles. In the form of filter cakes, diatomite contains about 10 percent solids and 90 percent voids.

Most of the diatomite produced in California is mined by two companies. Large deposits south of Lompoc are worked by the Johns-Manville Products Corporation. A deposit 7 miles southeast of Lompoc (fig. 6) and another in the Palos Verdes Hills, near Los Angeles, are worked by the Dicalite Division of Great Lakes Carbon Corporation.

The first diatomite quarried in southern California is believed to have been obtained from the Lompoc area in 1880, and is said to have been intended for use as a building stone. The low physical strength of diatomite precluded this application, but continued testing of the material led to its early use as a thermal insulator and as a filteraid in the beet-sugar industry. That the diatomite output has since increased at an accelerated rate is attributable to intensive research, largely by the producers, as well as to increases in population and industrialization. In the 28-year period from 1921 to 1949 the average yearly output of diatomite in southern California increased from 45,000 tons to 182,000 tons.

Diatomite was first shipped from the Lompoc area in 1892, but vigorous development of the deposits did not begin until 1912, when they were obtained by the Kieselguhr Company of America (a name

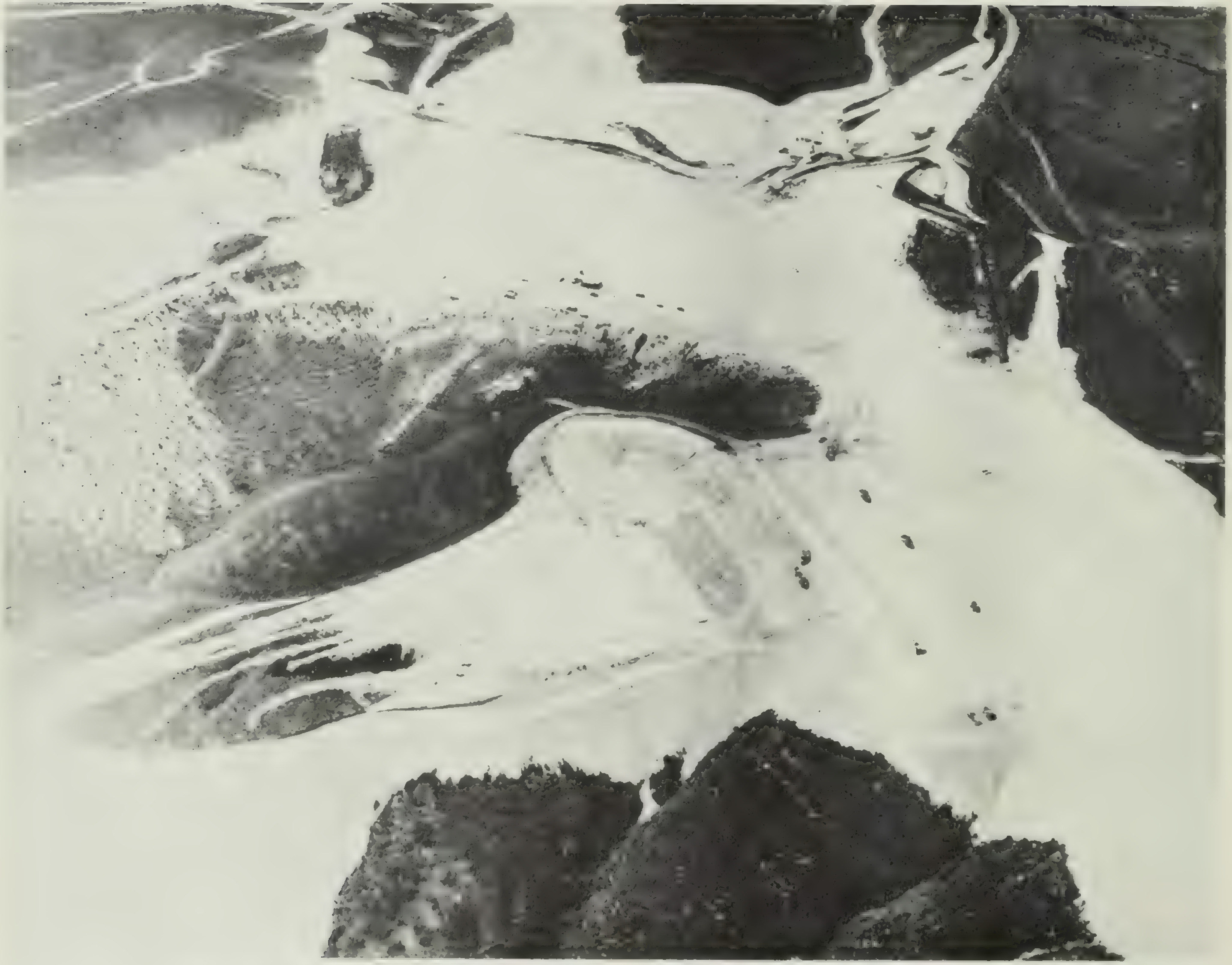

FIGURE 6. View northwestward of diatomite quarry operated by Dicalite Division of the Great Lakes Carbon Corporation, near Lompoc, Santa Barbara County. *Photo courtesy Great Lakes Carbon Corporation.*

Table 1. Summary of uses and sources of nonmetallic commodities in southern California.

Commodity	Principal uses in southern California	Principal current sources and geologic occurrence in southern California	Remarks
Asbestos **Chrysotile**	In automobile brake linings, clutch facings, gaskets, asbestos cement, asbestos cement shingles, magnesia insulation, filler, asphalt tile, paint extenders.	No current operations. Chrysotile occurences rare.	About 50,000 tons used annually in southern California. Most is short-fiber material obtained chiefly from eastern Canada and Arizona.
Amphibole	In noncorrosive acid filters.	No current operations. Formerly mined from alteration zones in Paleozoic dolomite in Inyo Mountains, Inyo County.	Local market very small.
Barite	In oil-well drilling mud, a filler in natural and synthetic rubber, in manufacture of lithopone, barium chemicals, and in glass.	No current operations. Small tonnages once mined from replacement deposits in limestone at Nine-mile Canyon, Inyo County, and from several sources in San Bernardino County.	Most of the barite shipped into southern California is from deposits in Nevada and Arizona.
Boron	In container glassware, ceramic glazes, porcelain enamel, soaps, cosmetics, disinfectants.	Bedded deposits of borax and kernite in Tertiary lake beds. Kramer district, Kern County. Recovered from brines of Searles Lake, San Bernardino County and Owens Lake, Inyo County.	Southern California provides about 95 percent of world's supply. Colemanite deposits in Tertiary nonmarine formations formerly mined in Death Valley area, Inyo County; Calico Mts., San Bernardino County; near Lang, Los Angeles County; and at Frazier Mt., Ventura County.
Bromine	Ethylene dibromide for antiknock gasoline; in grain and soil fumigants, and in photographic emulsions.	Recovered from alkali brine of Searles Lake. Bromine content of raw brine is 0.085 percent.	Consumption of bromine in southern California far exceeds production.
Calcium chloride	Accelerator in portland cement, in manufacture of agar agar, in refrigeration brine, oil-well drilling mud, ore treatment, dehumidification of walnuts.	Recovered from sodium-calcium chloride brine of Bristol Lake, San Bernardino County.	About 4,000 tons consumed annually in southern California.
Clays **Fire clay**	Clay of cone 27+ used in fire brick, ladle brick, fire-clay mortar, face tile, pottery. Clay of cone 19 to 27 used in sewer pipe and other heavy clay products.	Alberhill area, Riverside County, and Santa Ana Mts., Orange County. Layers and lenses in Paleocene sandstone.	Much of the higher-grade fire clay consumed in southern California is shipped from the Lincoln and Ione areas in the northern part of the state.
China clay	As a ceramic material in pottery, china ware and art ware. As a filler in paper, rubber, and roofing	Trabuco Canyon, Orange County; clay- and quartz-bearing lenses in Paleocene sandstone. Separated by hydraulic method.	Most of the china clay used in southern California is shipped from southeastern states and England.
Ball clay	In whiteware ceramics and wall tile.	Semi-plastic clay obtained from alteration zones in Tertiary rhyolite near Hart, San Bernardino County.	Output from California deposits used mostly in wall tile. Sources in Kentucky, Tennesee, and Florida contribute most of the ball clay consumed in southern California.
Bentonite (exclusive of bentonite used for bleaching)	In oil-well drilling mud, seal for dams and ditches, binder, filler, foundry material.	Known deposits of commercial bentonite are uncommon in southern California. Hectorite (high-magnesium bentonitic clay) mined from layers in Tertiary volcanic rocks near Newberry, San Bernardino County. Bentonite obtained intermittently from other deposits in Kern and San Bernardino Counties.	Swelling bentonite shipped to southern California from Wyoming and South Dakota. Non-swelling bentonite shipped from Mississippi.
Bleaching clay (includes Fuller's earth and activated bentonite)	Adsorbent for decolorizing and deodorizing oils and fats.	Olancha, Inyo County. Layer of altered volcanic rock in late Tertiary or Quaternary nonmarine sedimentary formation.	Annual consumption in southern California about 25,000 tons more than half of which is shipped from Arizona, Nevada, Mississippi, and Texas.
Common clay	Clay of cone 19 or less used in brick, sewer pipe, and cement.	Numerous operations, mostly in Recent alluvium in Los Angeles area.	About 500,000 tons consumed annually by ceramic industry from sources mostly in Los Angeles County. Common clay for use in cement is obtained near plants.
Diatomite	Filters, fillers, insulation.	Lompoc area, Santa Barbara County, and Palos Verdes Hills, Los Angeles County. Thick beds of diatomite in upper Miocene marine formations.	See accompanying text.
Dolomite	Roofing granules, blast furnace and foundry flux.	Victorville-Barstow area, San Bernardino County. Paleozoic carbonate units.	Most of the dolomite used in southern California is obtained from Paleozoic formations in southern Nevada.
Expanded shale	Light-weight aggregate.	Pliocene and Plio-Miocene sedimentary rocks in Santa Barbara and Ventura Counties.	See accompanying text.

Table 1. Summary of uses and sources of nonmetallic commodities in southern California—Continued.

Commodity	Principal uses in southern California	Principal current sources and geologic occurrence in southern California	Remarks
Feldspar	Various ceramic bodies.	Several small, widely scattered and intermittent operations in Mesozoic pegmatite dikes.	About 7,000 tons consumed annually in southern California. Most of this is shipped from a deposit near Kingman, Arizona. Feldspar formerly obtained from pegmatite dike near Campo, San Diego County, 1922-1942.
Gem stones	Mineral specimens and jewelry.	Beryl, garnet, quartz, spodumene, topaz, and tourmaline obtained from Mesozoic pegmatite dikes in San Diego and Riverside Counties. Operations small and intermittent; centered about Pala and Mesa Grande districts. Turquoise veins in granitic rock mined near Silver Lake, San Bernardino County, 1898-1903.	Large quantities of semiprecious gems and ornamental stones gathered by collectors in informal operations.
Gypsum	Building and industrial plaster products, retarder in portland cement, agricultural soil conditioner.	Gently folded beds in Tertiary formations, in Fish Creek Mts., Imperial County, and in northwestern Ventura County. Lenses and beds in Paleozoic (?) sedimentary rocks in Little Maria Mts., Riverside County. Gypsite mined from surficial deposits mainly in western San Joaquin Valley.	Competitive with out-of-state crude material and finished products. Gypsum shipped from Nevada and San Marcos Island, Mexico. Several hundred thousand tons consumed annually in southern California.
Iodine	Photographic materials, additive to food and medicine, laboratory reagents.	Waste brine from certain oil wells in Los Angeles basin.	Two producers in southern California contribute entire U. S. output of iodine and most of the iodine consumed in U. S.
Kyanite	In refractory ceramic bodies.	No current operations. Mined 1925-1946 from kyanite-quartz bodies in pre-Cambrian (?) complex near Ogilby, Imperial County.	Consumption small. Obtained mostly from southeastern United States and India.
Limestone	In portland cement manufacture, soil additives, and as metallurgical flux. In manufacture of quick lime and hydrated lime with numerous industrial uses. Source of CO_2 for brine carbonation.	Bodies of pre-Cretaceous crystalline limestone near Colton and Victorville, San Bernardino County; Riverside, Riverside County; Tehachapi, Kern County; Slate Range, Inyo County.	See accompanying text.
Lithium	In lubricants, enamel frits, air-conditioning equipment, Edison-type storage batteries, organic synthesis.	Recovered from alkali brine of Searles Lake, San Bernardino County. Lithium chloride content of brine 0.048 percent. Lepidolite formerly obtained from pegmatite bodies in San Diego County.	Searles Lake one of three major U. S. sources.
Magnesium chloride	In oxychloride cements.	Recovered at Chula Vista, San Diego County, from bittern obtained from nearby salt plant.	
Mica	As insulator in electrical equipment (sheet mica). In lubricants, roofing, and artificial snow (scrap mica). Roofing dust (muscovite schist).	No sheet- or scrap-mica operations in southern California. Mica schist mined from member of pre-Cambrian (?) complex near Ogilby, Imperial County.	Sheet and scrap mica shipped to southern California mainly from southeastern states and New England.
Perlite	Light-weight aggregate, filler, oil-well drilling and acidifying.	Late Tertiary to Recent volcanic rocks in Inyo, Kern, Riverside, and San Bernardino Counties.	See accompanying text.
Potassium salts	Commercial fertilizer.	Recovered from alkali brine of Searles Lake, San Bernardino County.	Searles Lake site of first commercial production of potassium salts in U. S. (1916). About 250,000 tons KCl produced annually. Most sent to out-of-state markets.
Pumice	Light-weight aggregate.	Late Tertiary to Recent volcanic rocks in Inyo, Kern, Imperial, and San Bernardino Counties.	See accompanying text.
Pyrophyllite	Insecticide carrier.	San Dieguito area, San Diego County. In lenticular bodies formed by alteration of Jurassic (?) volcanic rocks.	Pyrophyllite from deposits in Mono County also marketed in southern California. Deposits worked only since 1945.
Salt	Manufacture of chemicals, a preservative, reconditioner for zeolite water softeners, in refrigeration brine, and in foods.	Solar evaporation of sea water at San Diego Bay, San Diego County, and Newport Harbor, Orange County; also obtained from playas in San Bernardino and Kern Counties.	Much of the salt consumed in southern California shipped from solar evaporation plants on San Francisco Bay.
Sand and gravel	Concrete and plaster aggregate.	Recent alluvium in channels of Big Tujunga and San Gabriel Rivers of Los Angeles County, Lytle Creek and Santa Ana River of San Bernardino County and Otay River of San Diego County.	About 25 million tons mined and consumed annually in southern California. Operations numerous; many are short-lived.

Table 1. Summary of uses and sources of nonmetallic commodities in southern California—Continued.

Commodity	Principal uses in southern California	Principal current sources and geologic occurrence in southern California	Remarks
Sodium carbonate	Glass, industrial chemicals, soaps and cleansers.	Recovered from alkali brine of Searles Lake, San Bernardino County, and Owens Lake, Inyo County.	
Sodium sulfate	Manufacture of glass and synthetic detergents.	Alkali brine of Searles Lake, San Bernardino County. Formerly recovered from brine of Dale Lake, San Bernardino County.	More than 80 percent of U. S. output of natural sodium sulfate produced in southern California.
Special sands	Glass manufacture, foundry use, sand blasting.	Tertiary sandstone (glass); Tertiary sandstone and Quaternary alluvium and dune sand (foundry); Quaternary dune sand (sand blasting). Numerous operations.	High-silica sands shipped from Overton, Nevada, and Ottawa, Illinois.
Stone	Concrete aggregate, road metal, breakwaters and fill protection, roofing granules, furnace flux (limestone), and dimension stone in buildings.	Numerous quarries, mostly in various pre-Cretaceous rocks and Tertiary volcanic rocks, throughout southern California.	About 5,000,000 tons consumed annually in southern California.
Strontium	Little or no strontium now consumed in southern California. Was used in manufacture of pyrotechnical products.	No present production.	Largest known celestite reserves in United States occur in Tertiary lake beds near Ludlow, San Bernardino County.
Sulfur	Manufacture of sulfuric acid, compounding of rubber, in insecticides, paper manufacture, and as an agricultural mineral.	Recovered from waste gas of petroleum refineries. Small output mined from irregular bodies in Tertiary volcanic and sedimentary rocks and Paleozoic limestone in Last Chance Range, Inyo County.	All but a small part of the 200,000 tons (estimated figure) of sulfur used annually in southern California is shipped from Texas.
Talc	Ceramic raw material, wall tile, electrical insulators, pottery, and artware. Paint extender, filler, insecticide carrier.	Tabular to lenticular bodies altered from Paleozoic and pre-Cambrian carbonate rocks in Inyo and San Bernardino Counties.	See accompanying text.
Volcanic cinders (scoria)	Light-weight aggregate.	Recent volcanic cones in Inyo and San Bernardino Counties.	See accompanying text.

later changed to Celite Products Company). The Johns-Manville Products Corporation acquired the property in 1928.

The deposits in the Palos Verdes Hills were opened in 1929, when the Dicalite Company leased the property and constructed a plant. In 1944 this company was purchased by the Great Lakes Carbon Corporation, and thereafter became known as the Dicalite Division of that corporation. During World War II the Dicalite Division opened a deposit east of Lompoc, and for several years trucked crude diatomite from the mine to its processing plant at Walteria, near Los Angeles. In 1952 a 2.7-million dollar plant was placed in operation near Lompoc.

The diatomite deposits near Lompoc, the largest known in California, are in the northern foothills of the Santa Ynez Mountains in southwestern Santa Barbara County. The deposits, including those in the Santa Ynez Valley and Santa Rita Hills east of Lompoc, underlie areas that total about 17 square miles. The best commercial material has been mined from pure, thinly stratified diatomite in the lower 1,000 feet of the Sisquoc formation (Dibblee, 1950, pp. 75-77). The diatomite beds at the northern margin of the Lompoc and Santa Rita Hills occur mainly in a group of outliers that rest, with depositional contact, upon the Monterey formation. Immediately south and west of the town of Lompoc the diatomite beds dip northward beneath Quaternary beds of the Lompoc Valley. Impure, coarsely stratified and massive types of diatomite are abundant, but to date have not proved to be of significant commercial value.

Smaller diatomite deposits of possible commercial value are present in the eastern Purisima Hills near Solvang and in the area east of Santa Ynez. Beds in the Santa Ynez area are overlain by terrace deposits, and hence the extent of commercial material is unknown.

The deposits in the Palos Verdes Hills area, in southwestern Los Angeles County, are exposed on the north flank and crest of the hills, the structure of which is principally anticlinal. Here the material is quarried from the upper part of the Valmonte diatomite member of the Monterey shale (upper Miocene) (Woodring, Bramlette, and Kew, 1946, pp. 120-121). Commercial diatomite is mined from several layers that are separated from one another by a hundred or more feet of noncommercial diatomaceous mudstone. The diatomite mined through 1953 was removed from quarries low on the hills, but late in 1953 the company was granted permission to open undeveloped deposits near the crest.

Other deposits of marine diatomite, also Miocene in age, have been worked on a small scale on Catalina Island, in the San Jose Hills near Covina, Los Angeles County, and in Orange County. Fresh-water diatomite has been mined in minor amounts from Tertiary lake deposits near Zurich, in Inyo County. Large reserves of fresh-water diatomite, as yet unexploited, occur in other parts of the State.

A great deal of care is exercised in the mining and treatment of diatomite. Open-pit methods involving power equipment are employed in the present operations, but for many years hand quarrying and underground mining were common. Earth-moving equipment of large capacity has enabled the operators to handle increased tonnages economically. Sawing of insulating bricks from quarry faces was introduced in the Lompoc area by Robert Graham in 1908. This method was only recently discontinued by the major producers. Quarrying is a selective specialized part of the operation, as certain beds of diatomite are suitable for particular products. As many as a hundred layers are removed separately in a single quarry (Leppla, 1953, p. 3).

Processed diatomite is marketed in many grades, which differ principally in particle size and size distribution. All grades are crushed, dried, treated by air separation to remove oversize impurities, and air classified. For use in insulation, as filter aids, and as abrasives, the diatomite is calcined at temperatures of 1,200° to 2,000° F. in order to remove water and oxidize any iron that is present. Some of the diatomite also is treated chemically. Material to be used as filteraid ordinarily is again air classified, and is passed through as many as twelve cyclone separators and collectors.

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BULL. 170 CHAPT. 6
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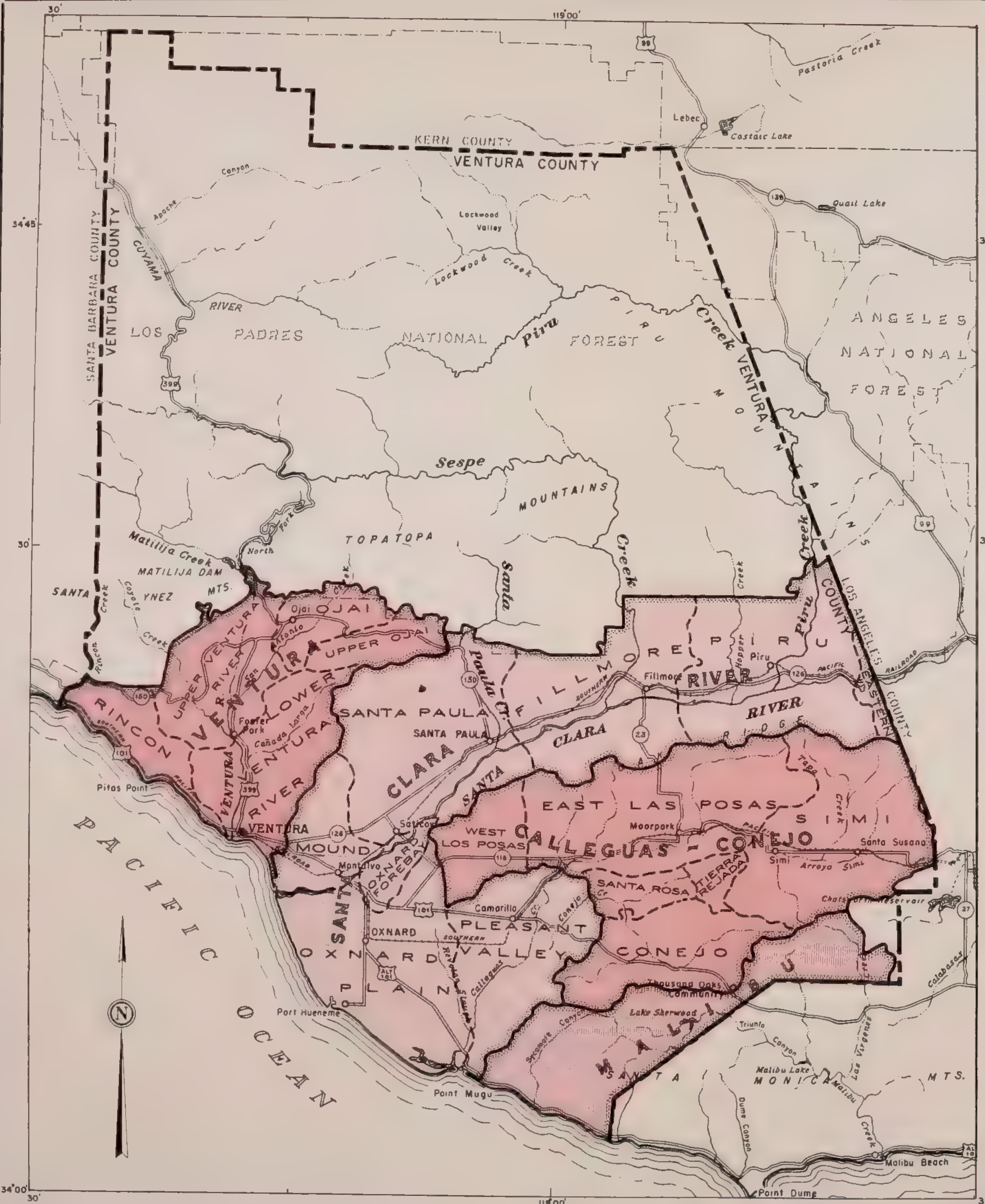
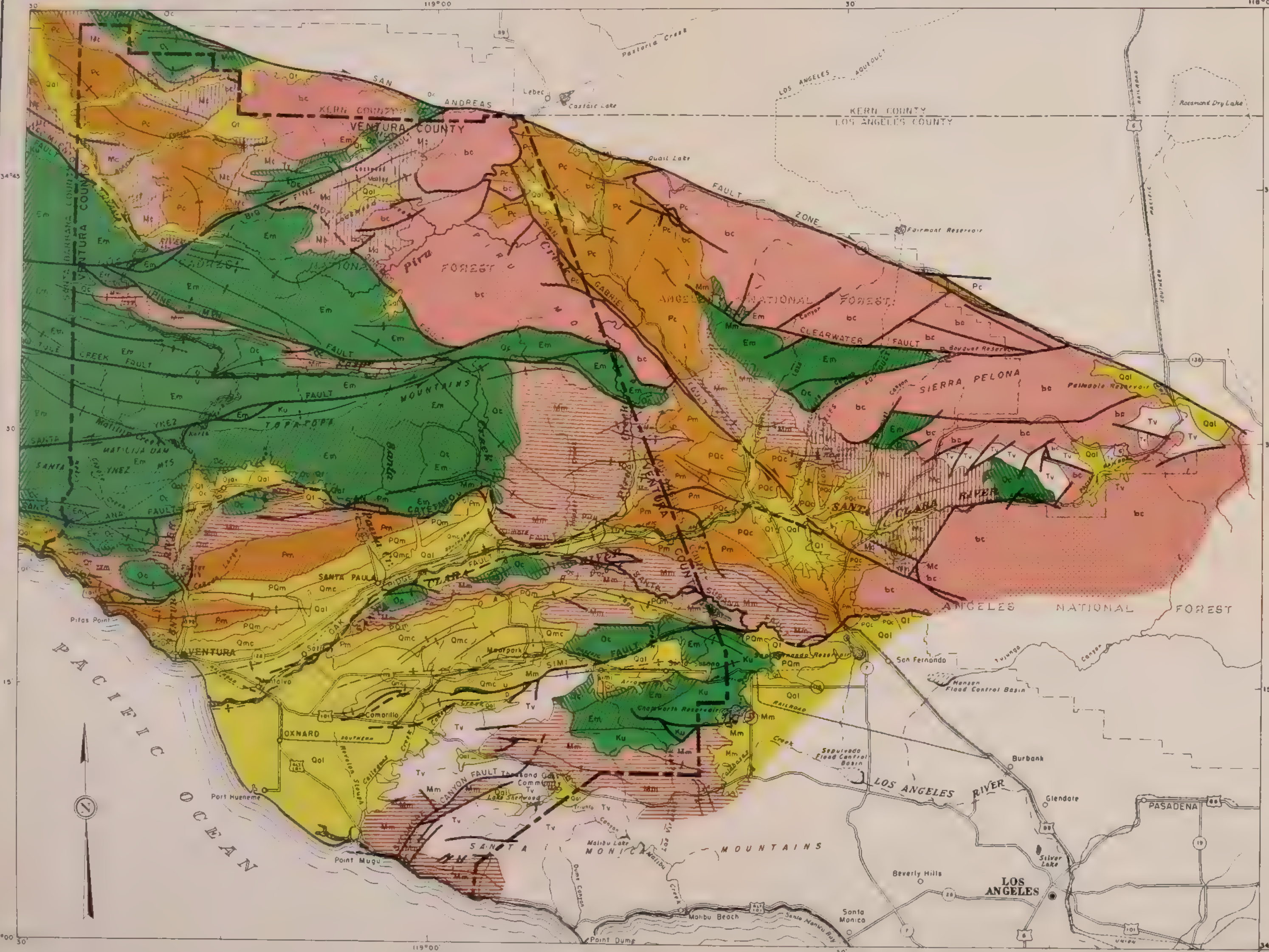


LOCATION MAP

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
VENTURA COUNTY INVESTIGATION

HYDROLOGIC UNITS
1953



GEOLOGIC LEGEND

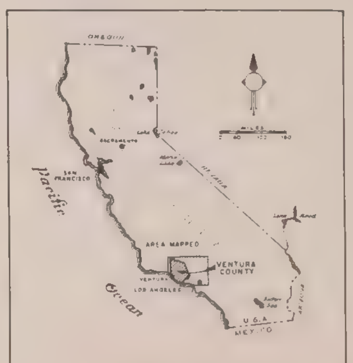
SEDIMENTARY FORMATIONS

RECENT	Qal	ALLUVIUM SAND, GRAVEL AND CLAY IN STREAM CHANNELS AND FLOOD PLAINS SUPPLIES MANY WELLS	QUATERNARY
	Qt	TERRACE DEPOSITS AND OLDER ALLUVIUM GRAVEL, SAND AND CLAY GENERALLY HIGHLY PERMEABLE, SUPPLIES MANY WELLS	
PLEISTOCENE	Qmc	SAN PEDRO FORMATION SAND, GRAVEL AND CLAY MARINE AND CONTINENTAL PERMEABLE ZONES SUPPLY MANY WELLS, INCLUDES FOX CANYON MEMBER WHICH YIELDS CONSIDERABLE WATER OF GOOD QUALITY IN THE LAS POSAS AND PLEASANT VALLEY AREAS	
	PQm	SANTA BARBARA FORMATION MARINE MUDSTONE, SHALE, SANDSTONE, SAND, GRAVEL AND CLAY. NONWATER-BEARING EXCEPT FOR GRIMES CANYON MEMBER WHICH SUPPLIES SOME WELLS IN THE LAS POSAS—PLEASANT VALLEY AREA	TERTIARY
PLIOCENE	PQc	SAUGUS FORMATION SAND, SLIGHTLY CEMENTED GRAVEL AND CLAY. CONTAINS MODERATELY PERMEABLE STRATA, YIELDS WATER TO FEW WELLS	
	Pm	PICO FORMATION MARINE SANDSTONE, SHALE, LENSES OF CONGLOMERATE GENERALLY NONWATER-BEARING OR CONTAINS SALTY WATER.	
	Pc	RIDGE BASIN GROUP AND MORALES FORMATION CONTINENTAL SHALE, SANDSTONE, CONGLOMERATE, GRAVEL AND SAND CONTAINS UNDEVELOPED PERMEABLE ZONES	
MIOCENE	Mm	SANTA MARGARITA, MODELO, RINCON AND VAQUEROS FORMATIONS MARINE SANDSTONE AND SHALE, SOME CONGLOMERATE AND CLAY. GENERALLY NONWATER-BEARING OR CONTAINS BRACKISH WATER. LOCALLY PROVIDES LIMITED QUANTITIES OF FRESH WATER TO WELLS	
	Mc	MINT CANYON AND QUATAL FORMATIONS NON-MARINE SANDSTONE, CONGLOMERATE, GYPSIFEROUS CLAY AND SOME MARL GENERALLY NONWATER-BEARING	
OLIGOCENE	Oc	SESPE, SIMMLER AND VASQUEZ FORMATIONS NON-MARINE SANDSTONE, CONGLOMERATE AND SHALE GENERALLY NONWATER-BEARING OR CONTAINS BRACKISH WATER, SUPPLIES FEW WELLS LOCALLY	
EOCENE AND PALEOCENE	Em	UNDIFFERENTIATED EOCENE AND PALEOCENE FORMATIONS MARINE SANDSTONE, SHALE AND CONGLOMERATE. PERMEABLE ZONES YIELD LIMITED QUANTITIES OF VARIABLE QUALITY WATER	
	Ku	UNDIFFERENTIATED MARINE FORMATIONS SANDSTONE, SHALE AND LITTLE CONGLOMERATE. PERMEABLE ZONES IN SOME AREAS YIELD WATER OF VARIABLE QUALITY IN LIMITED AMOUNT	CRETACEOUS

IGNEOUS AND METAMORPHIC ROCKS

Tv	VOLCANIC FLOWS, PYROCLASTICS, AND SHALLOW INTRUSIVES YIELDS VARIABLE QUANTITIES OF WATER TO WELLS. IMPORTANT WATER SOURCE IN SANTA ROSA, TIERRA REJADA AND CONEJO AREAS	TERTIARY
bc	BASEMENT COMPLEX GRANITIC AND METAMORPHIC ROCKS NONWATER-BEARING EXCEPT FOR LIMITED QUANTITIES OF WATER DERIVED FROM FISSURES OR WEATHERED ZONES	PRE-CRETACEOUS

━━━	FAULT, SURFACE TRACE
━ ━ ━	FAULT, BURIED OR INFERRED
─┼─	AXIS OF ANTICLINE (DASHED WHERE BURIED)
─┼─	AXIS OF SYNCLINE (DASHED WHERE BURIED)
∼∼∼	FORMATION CONTACT



LOCATION MAP

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STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
VENTURA COUNTY INVESTIGATION

AREAL GEOLOGY

1953

MILES
0 1 2 4 6 8 10

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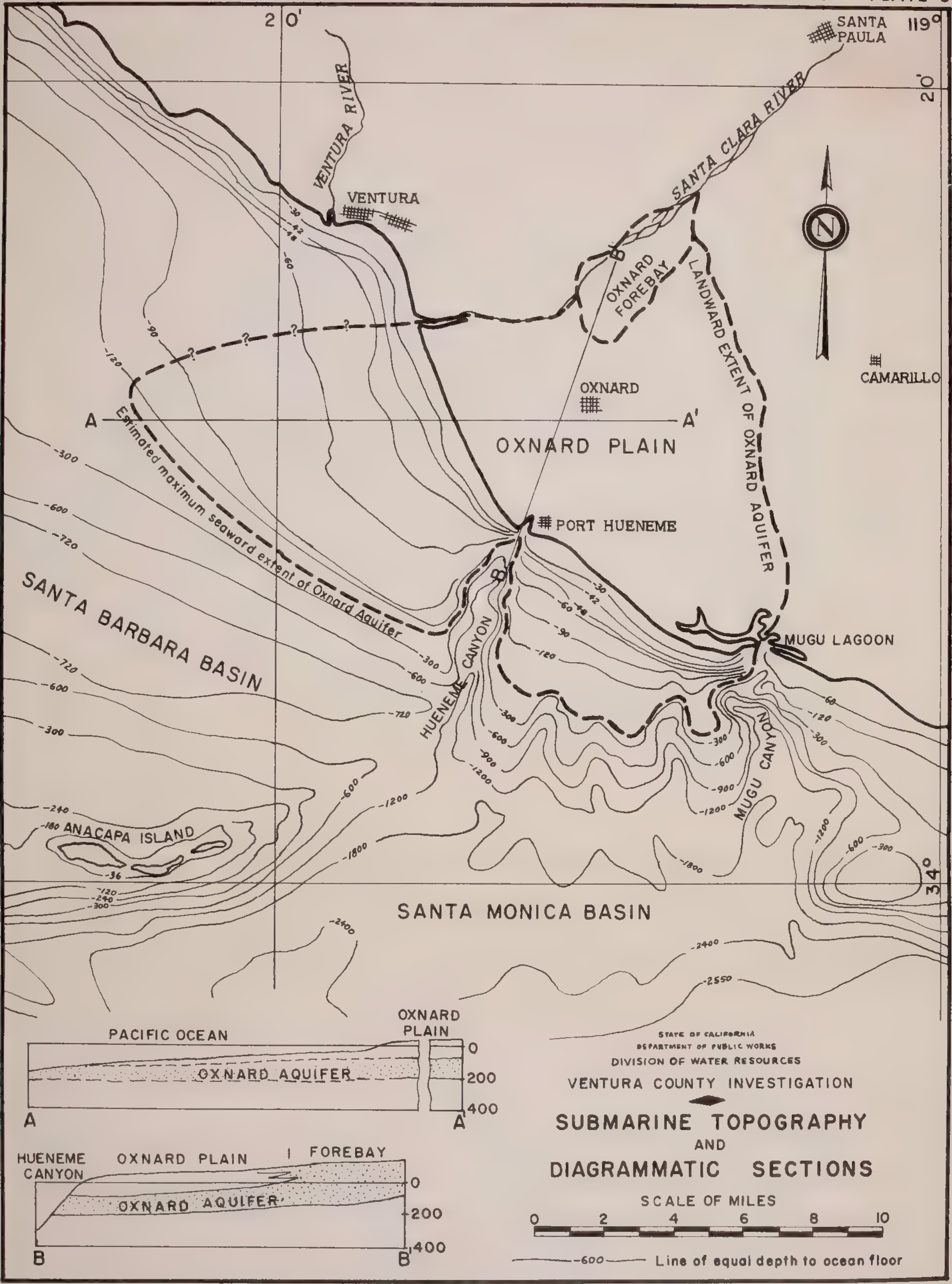
BULL. 170 CHAPT. 6
CONTRIB. 3 PLATE 3



STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

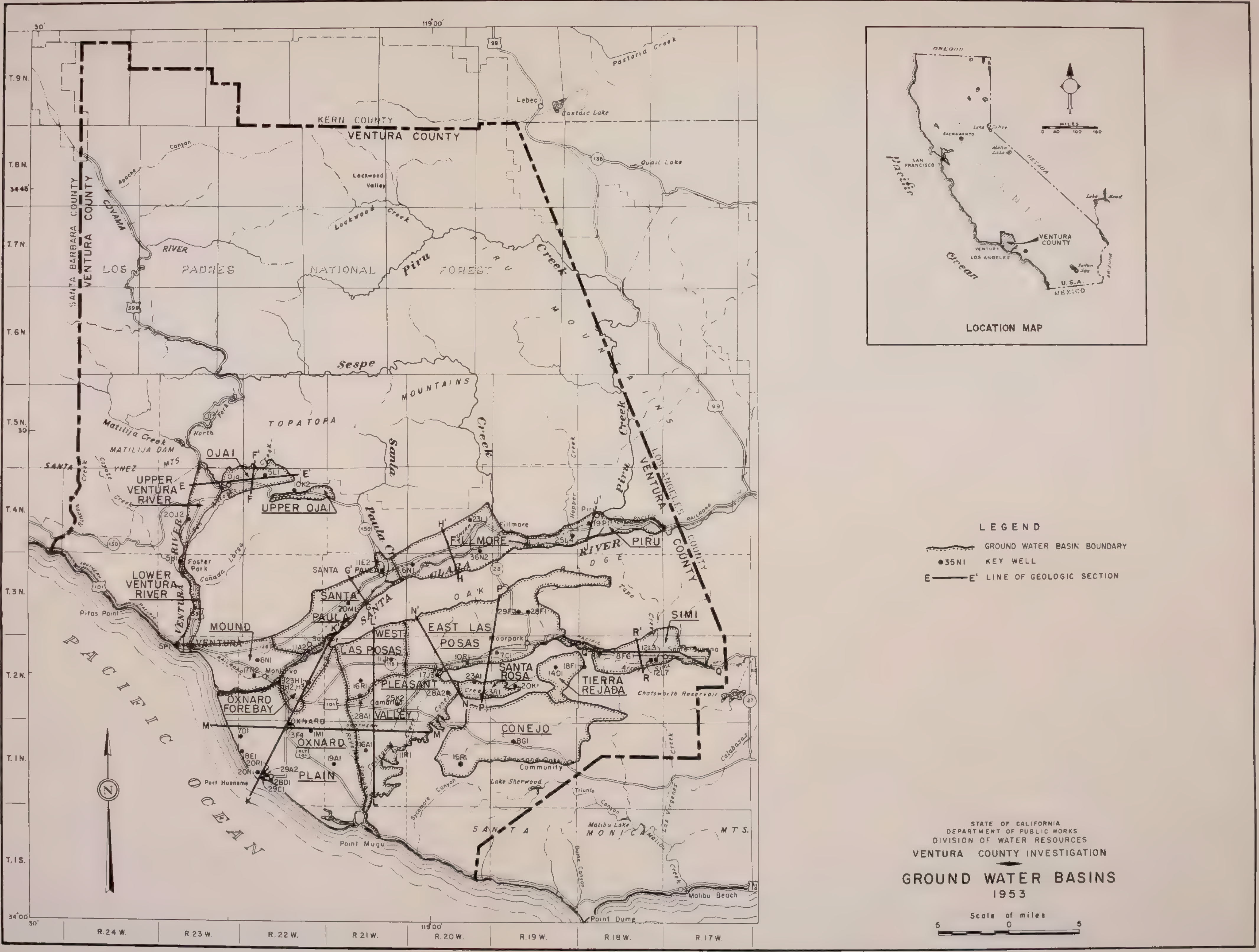
VENTURA COUNTY INVESTIGATION

◆

SUBMARINE TOPOGRAPHY
AND
DIAGRAMMATIC SECTIONS

SCALE OF MILES
0 2 4 6 8 10

—600— Line of equal depth to ocean floor



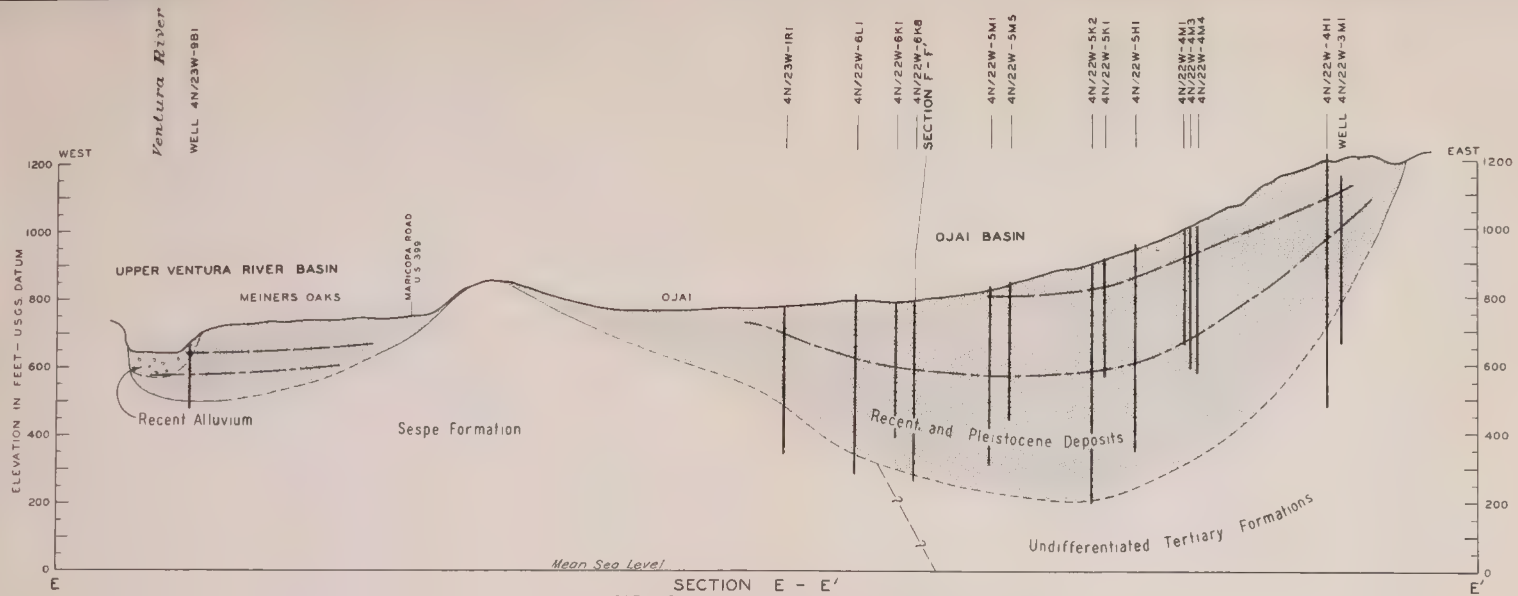
LEGEND

GROUND WATER BASIN BOUNDARY
●35N1 KEY WELL
E———E' LINE OF GEOLOGIC SECTION

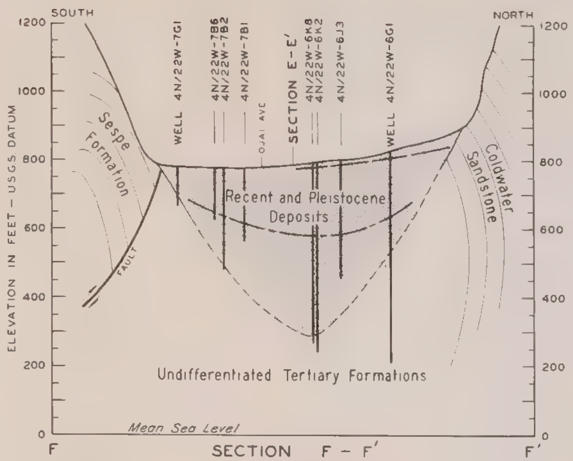
STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
VENTURA COUNTY INVESTIGATION

GROUND WATER BASINS
1953

Scale of miles
5 0 5



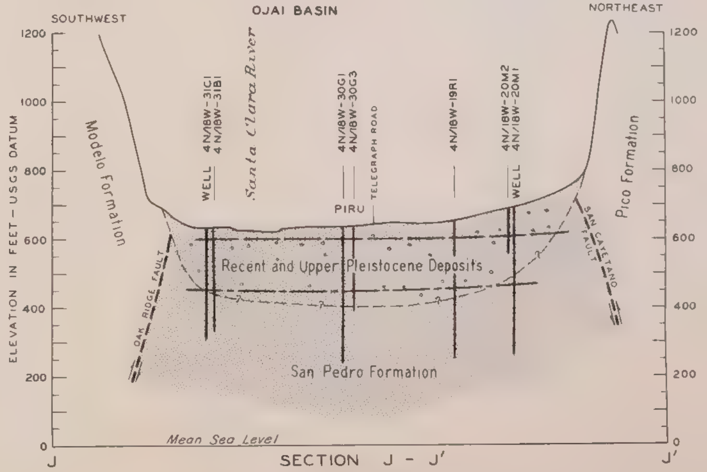
SECTION E – E'
UPPER VENTURA RIVER AND OJAI BASINS



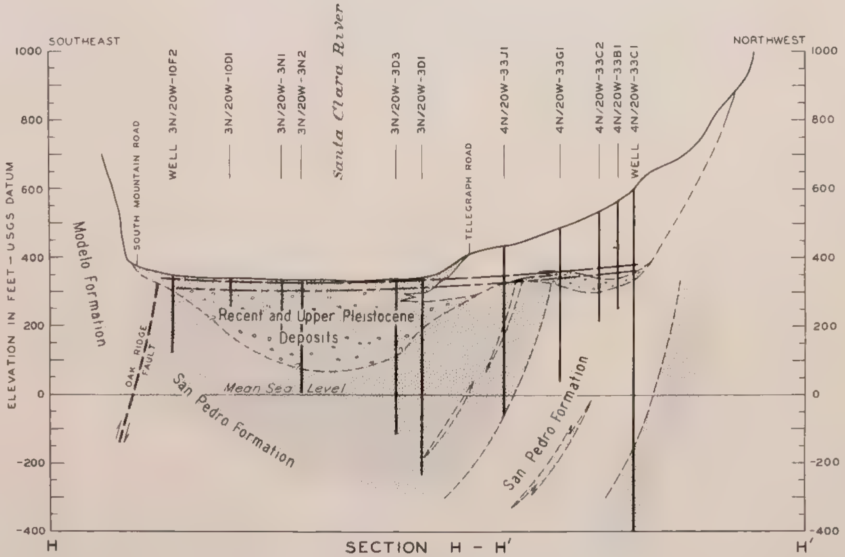
SECTION F – F'
OJAI BASIN

LEGEND

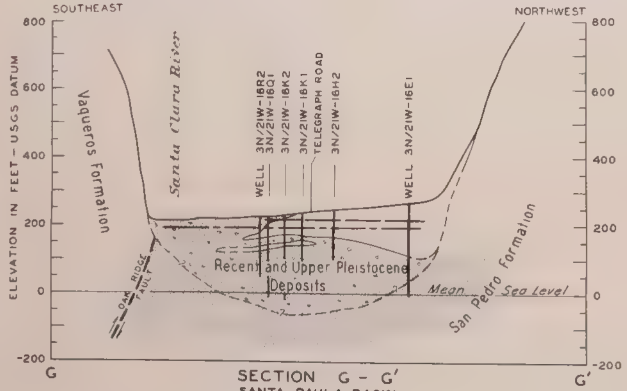
- ☐ DEPOSITS OF LOW PERMEABILITY
- ▨ RECENT AND UPPER PLEISTOCENE DEPOSITS
- ▨ FOX CANYON AQUIFER AND UNDIFFERENTIATED PLEISTOCENE DEPOSITS
- ▨ GRIMES CANYON AQUIFER
- | WATER WELL
- Spring 1944 / Fall 1951 APPROXIMATE LEVEL OF WATER IN WELLS



SECTION J – J'
PIRU BASIN



SECTION H – H'
FILLMORE BASIN



SECTION G – G'
SANTA PAULA BASIN

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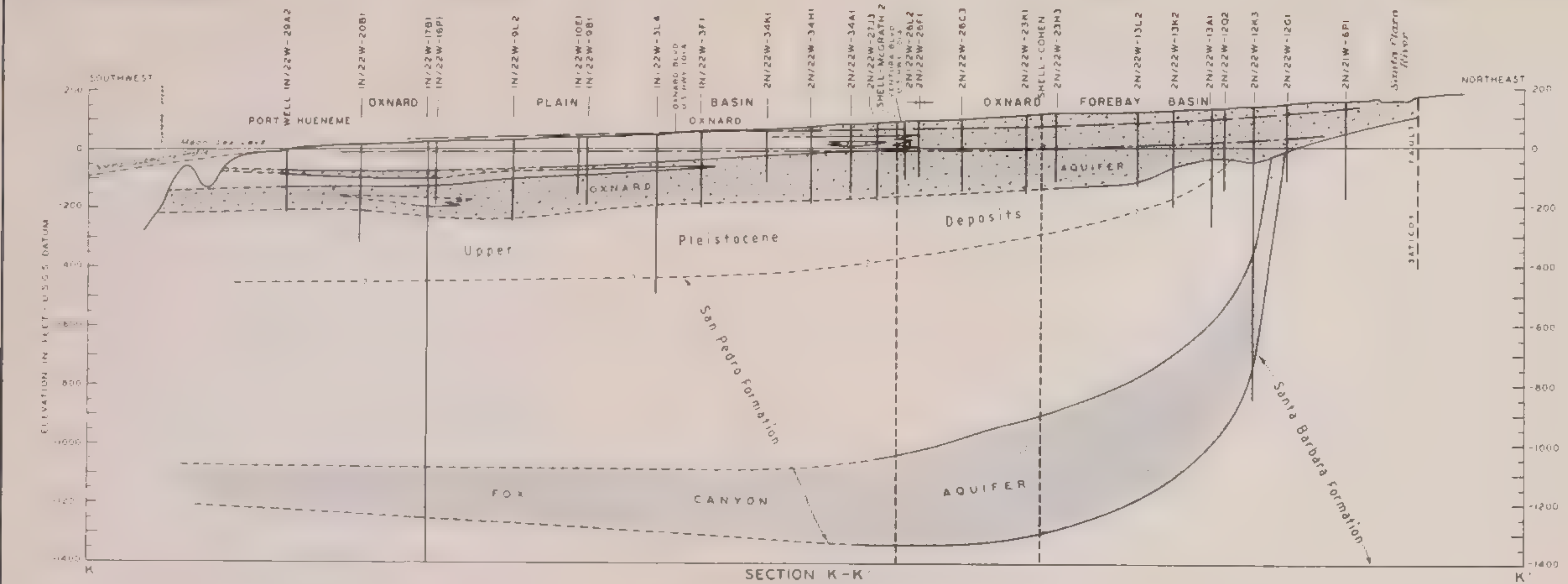
VENTURA COUNTY INVESTIGATION

◆

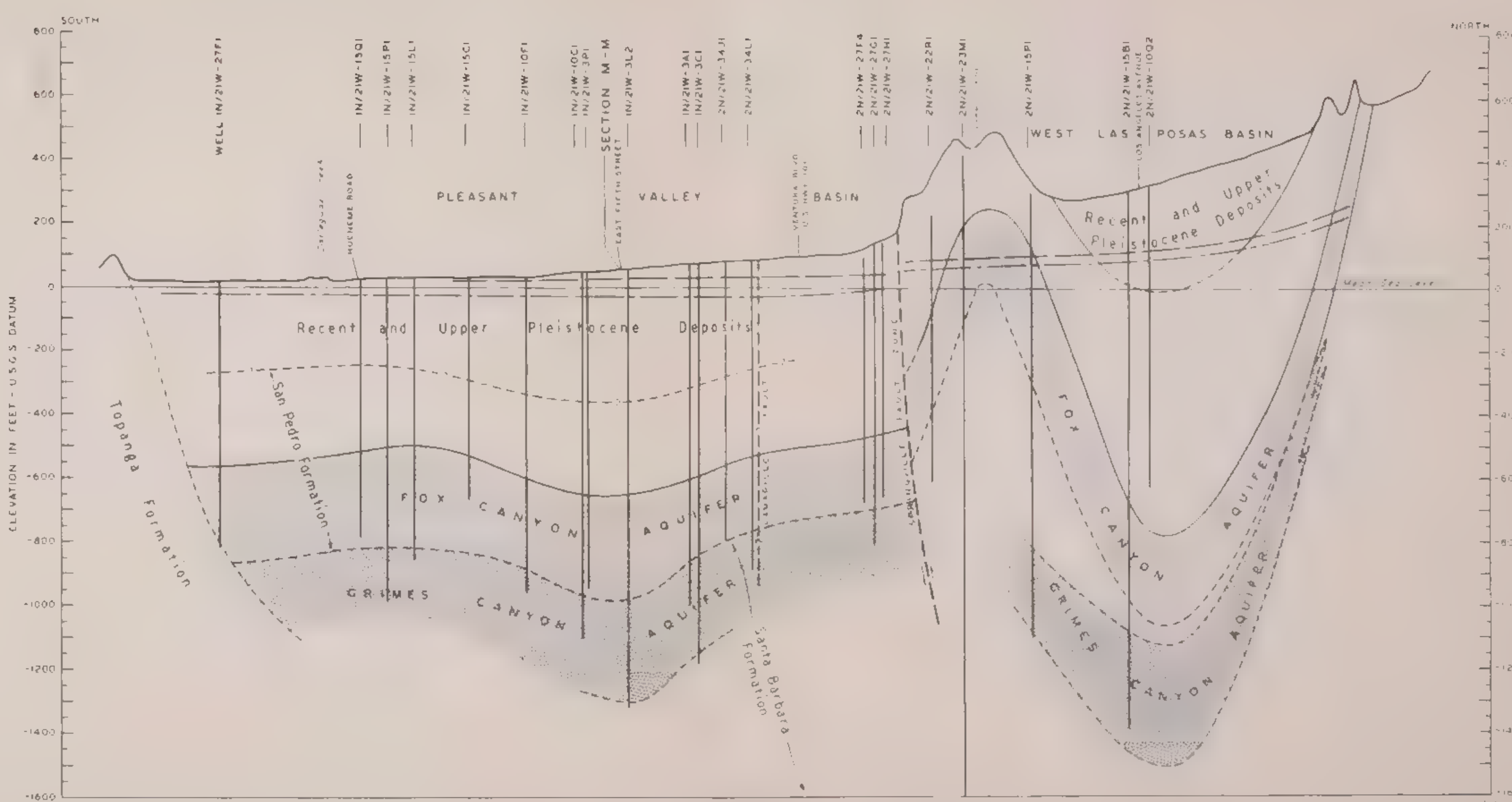
GEOLOGIC SECTIONS
E-E', F-F', G-G', H-H' AND J-J'
1953

HORIZONTAL
SCALE 2000 0 2000 4000 6000 FEET

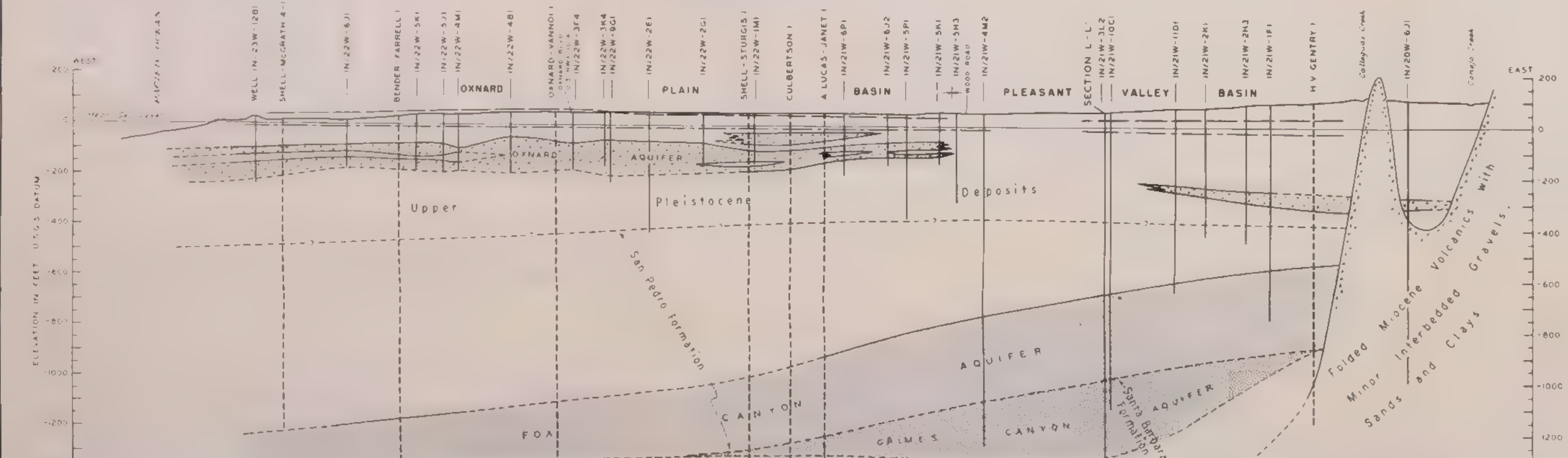
NOTE: PLAN OF SECTIONS SHOWN ON PLATE 4



SECTION K-K'
OXNARD PLAIN AND OXNARD FOREBAY BASINS



SECTION L-L'
PLEASANT VALLEY AND WEST LAS POSAS BASINS



SECTION M-M'
OXNARD PLAIN AND PLEASANT VALLEY BASINS

LEGEND

- ▭ DEPOSITS OF LOW PERMEABILITY
- ▨ RECENT AND UPPER PLEISTOCENE DEPOSITS
- ▭ FOX CANYON AQUIFER AND UNDIFFERENTIATED PLEISTOCENE DEPOSITS
- ▨ GRIMES CANYON AQUIFER
- | WATER WELL
- ¦ OIL WELL
- APPROXIMATE LEVEL OF WATER IN WELLS

NOTE: PLAN OF SECTIONS SHOWN ON PLATE 4

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES
VENTURA COUNTY INVESTIGATION

GEOLOGIC SECTIONS
K-K', L-L' AND M-M'
1953

HORIZONTAL
SCALE 2000 0 2000 4000 6000 FEET

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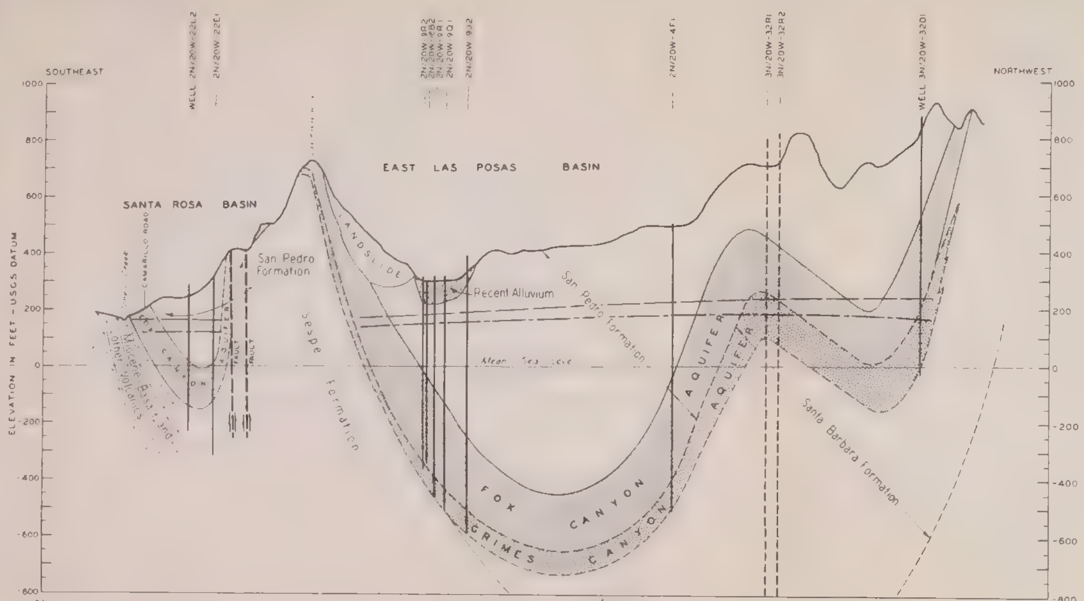
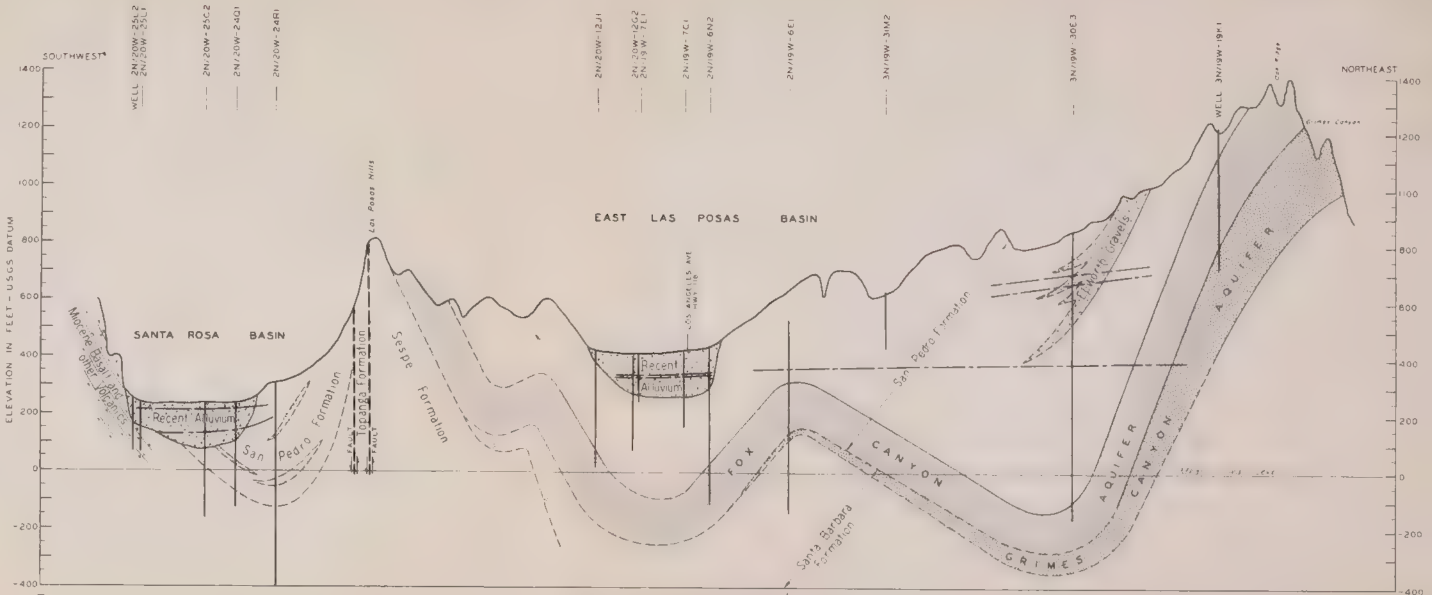
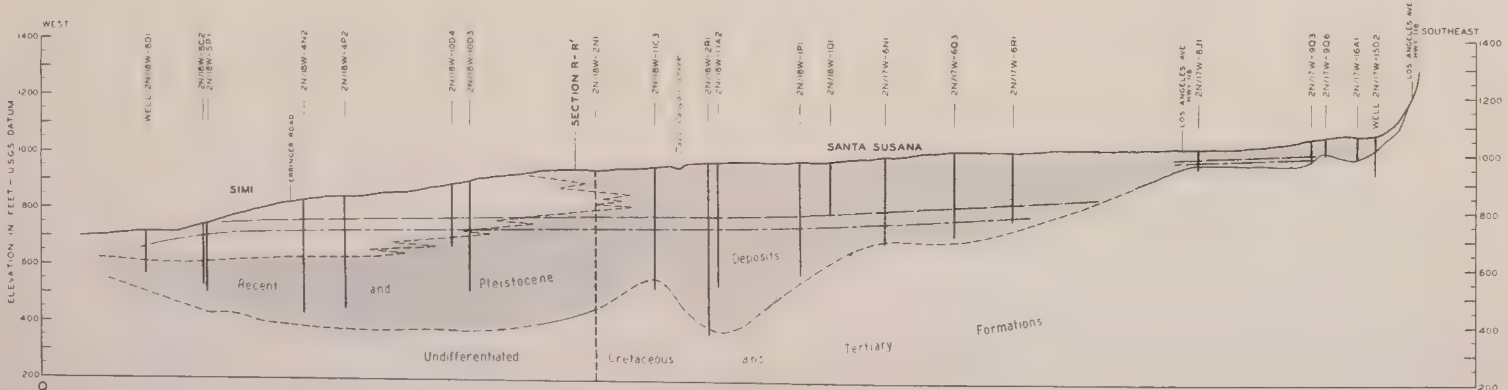
24
C3
A3
no.17
c.3



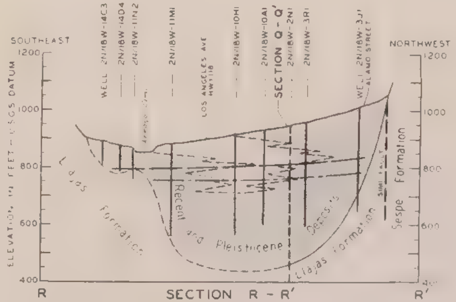
SECTION N - N'
SANTA ROSA AND EAST LAS POSAS BASINS



SECTION P - P'
SANTA ROSA AND EAST LAS POSAS BASINS



SECTION Q - Q'
SIMI BASIN



SECTION R - R'
SIMI BASIN

LEGEND

▭ DEPOSITS OF LOW PERMEABILITY
▨ RECENT AND UPPER PLEISTOCENE DEPOSITS
▭ FOX CANYON AQUIFER AND UNDIFFERENTIATED PLEISTOCENE DEPOSITS
▨ GRIMES CANYON AQUIFER
| WATER WELL
¦ OIL WELL
— APPROXIMATE LEVEL OF WATER IN WELLS

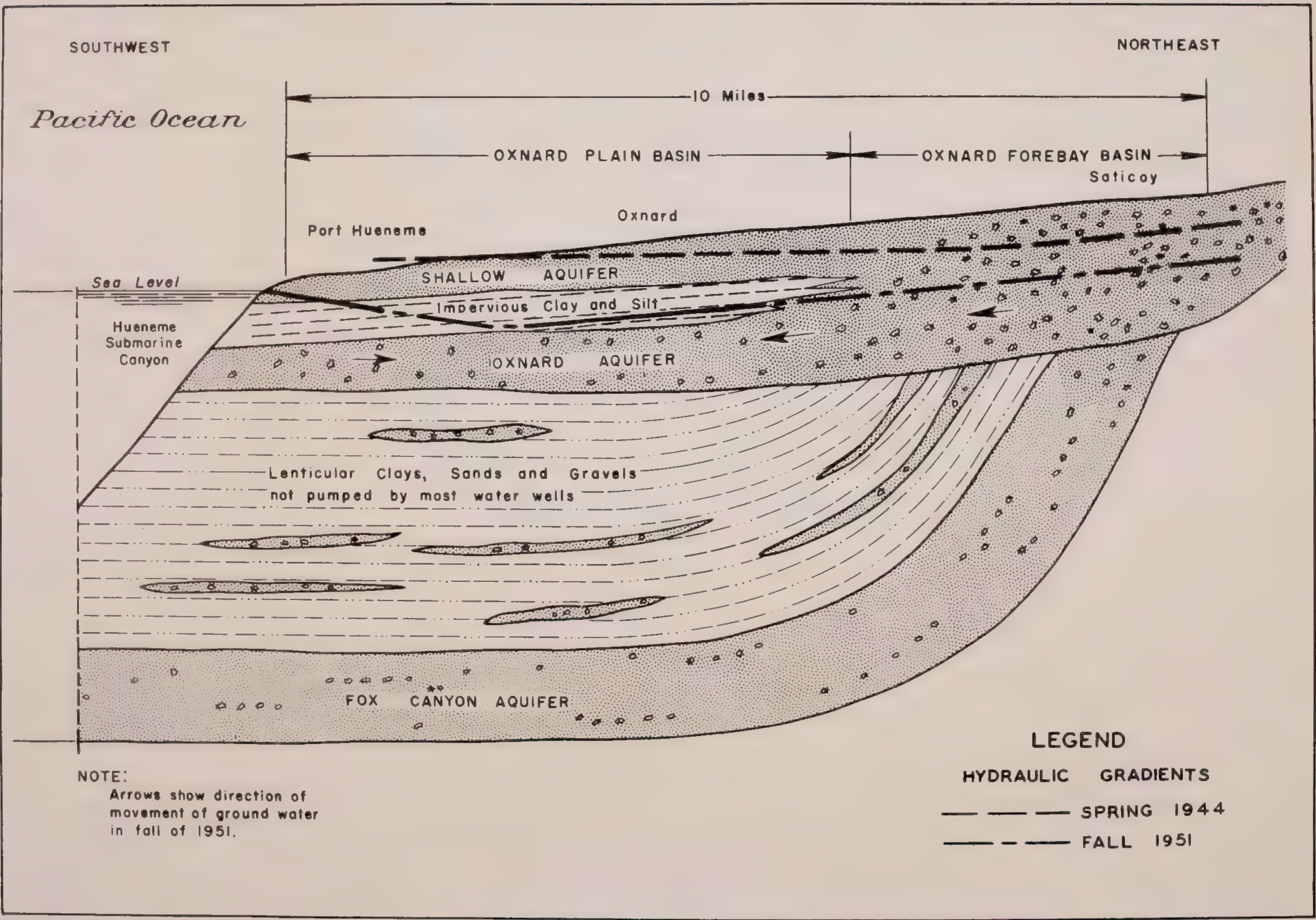
STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

VENTURA COUNTY INVESTIGATION

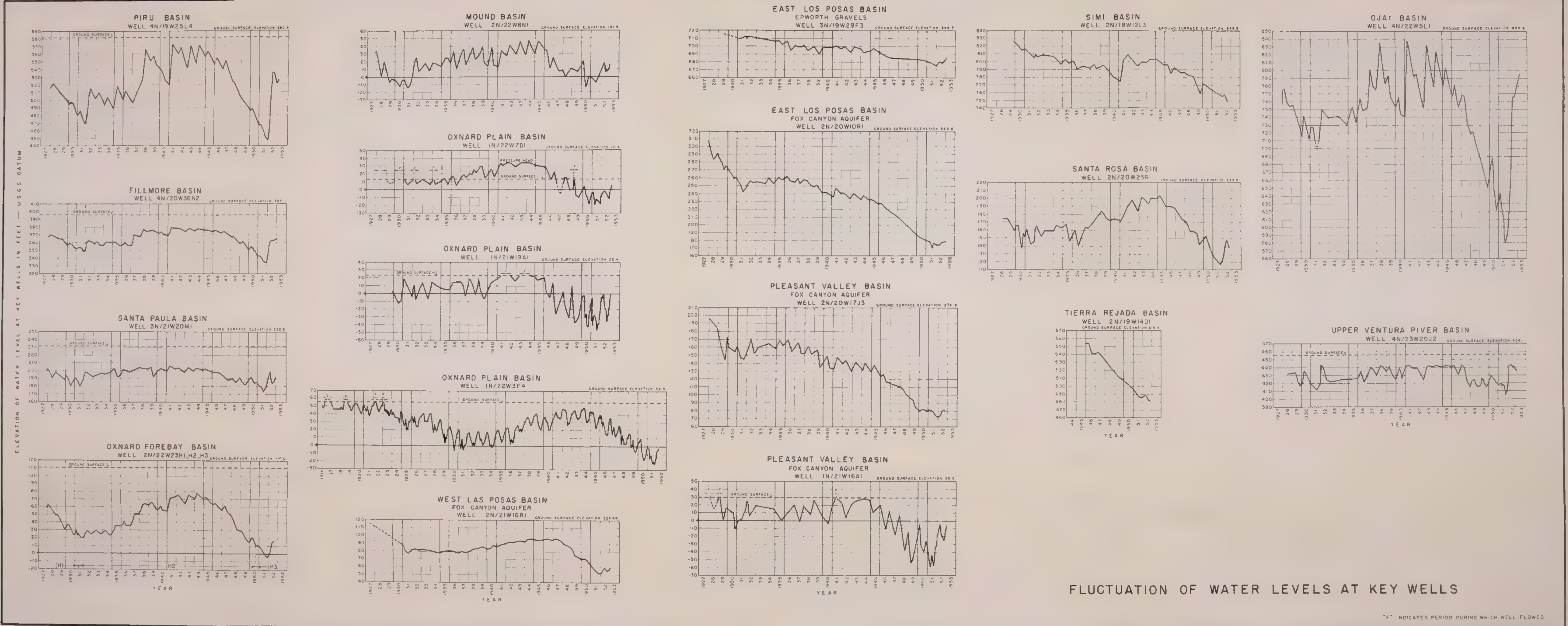
GEOLOGIC SECTIONS
N-N', P-P', Q-Q' AND R-R'
1953

HORIZONTAL
SCALE 2000 0 2000 4000 6000 FEET

NOTE: PLAN OF SECTIONS SHOWN ON PLATE 4



NOTE:
Arrows show direction of movement of ground water in fall of 1951.



PIRU BASIN
WELL 4N/19W25L4

FILLMORE BASIN
WELL 4N/20W36N2

SANTA PAULA BASIN
WELL 3N/21W20M1

OXNARD FOREBAY BASIN
WELL 2N/22W23H1,H2,H3

MOUND BASIN
WELL 2N/22W8N1

OXNARD PLAIN BASIN
WELL 1N/22W7D1

OXNARD PLAIN BASIN
WELL 1N/21W19A1

OXNARD PLAIN BASIN
WELL 1N/22W3F4

WEST LAS POSAS BASIN
FOX CANYON AQUIFER
WELL 2N/21W16R1

EAST LOS POSAS BASIN
EPWORTH GRAVELS
WELL 3N/19W29F3

EAST LOS POSAS BASIN
FOX CANYON AQUIFER
WELL 2N/20W10R1

PLEASANT VALLEY BASIN
FOX CANYON AQUIFER
WELL 2N/20W17J3

PLEASANT VALLEY BASIN
FOX CANYON AQUIFER
WELL 1N/21W16A1

SIMI BASIN
WELL 2N/18W12L3

SANTA ROSA BASIN
WELL 2N/20W23R1

TIERRA REJADA BASIN
WELL 2N/19W14D1

OJAI BASIN
WELL 4N/22W5L1

UPPER VENTURA RIVER BASIN
WELL 4N/23W20J2

FLUCTUATION OF WATER LEVELS AT KEY WELLS

"F" INDICATES PERIOD DURING WHICH WELL FLOWED

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24
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A3
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c.3

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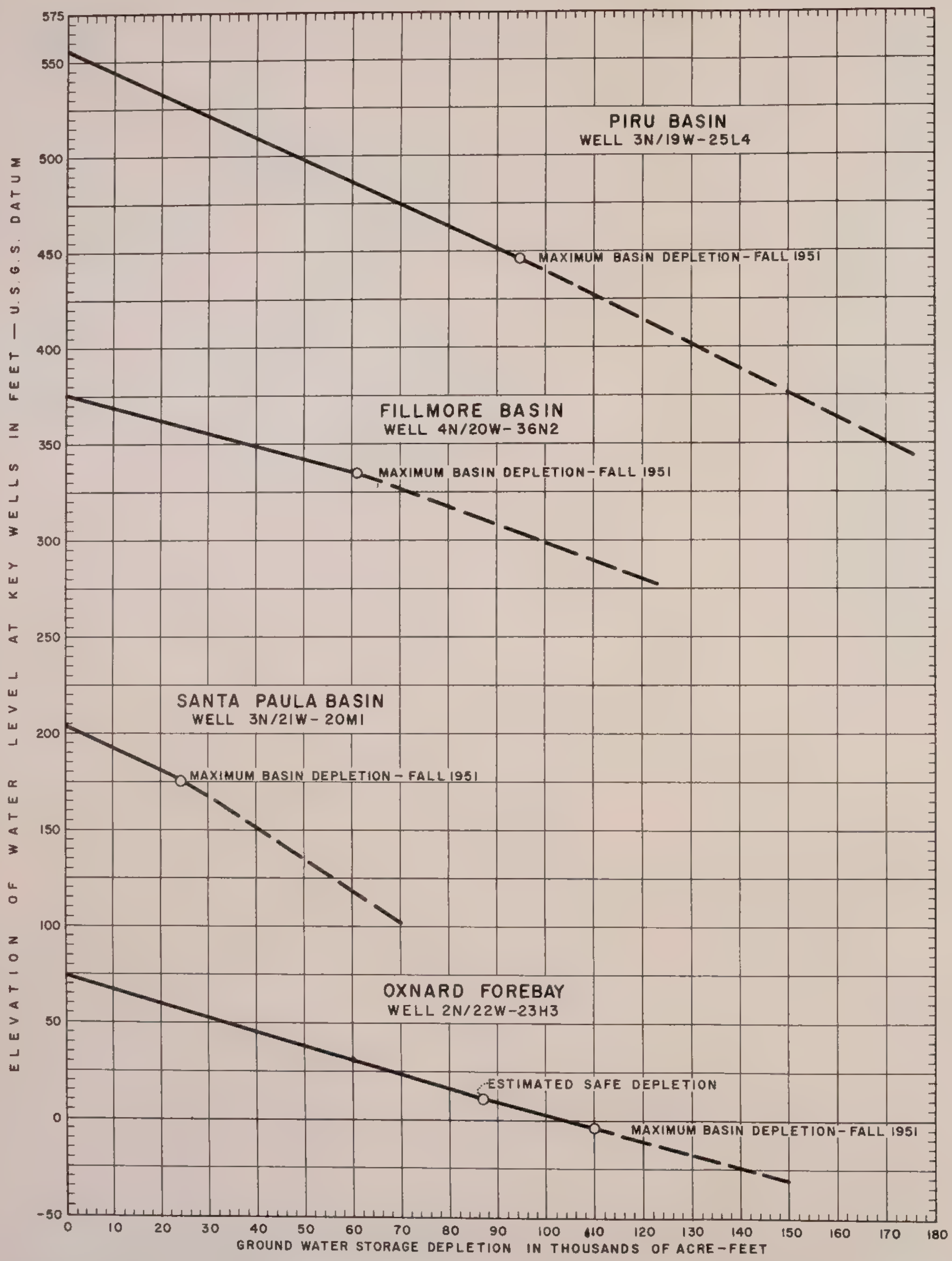
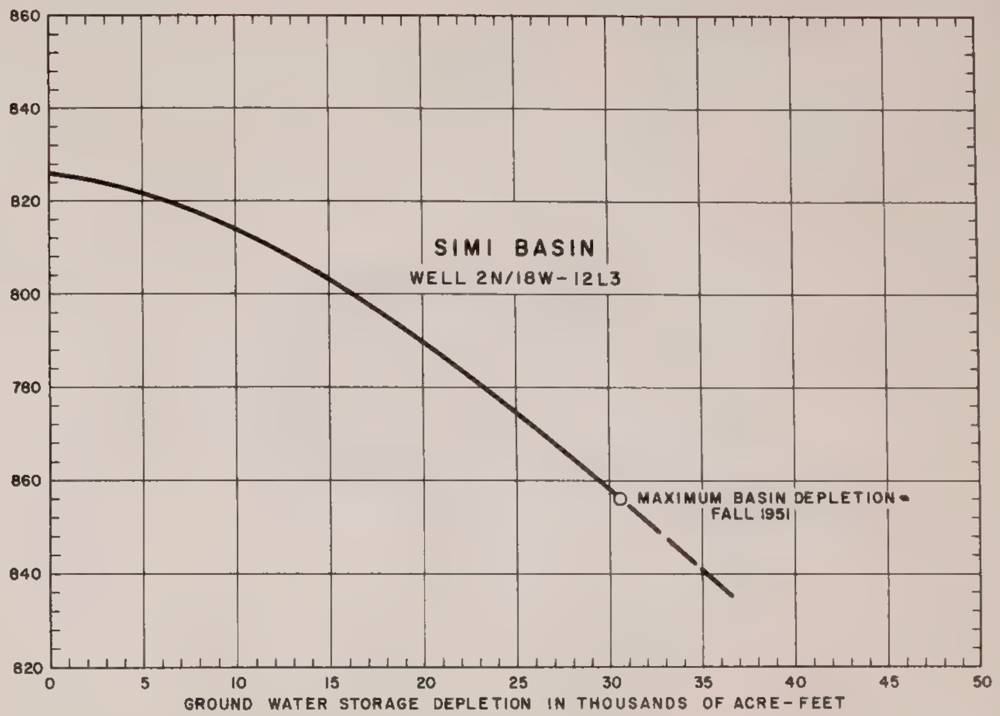
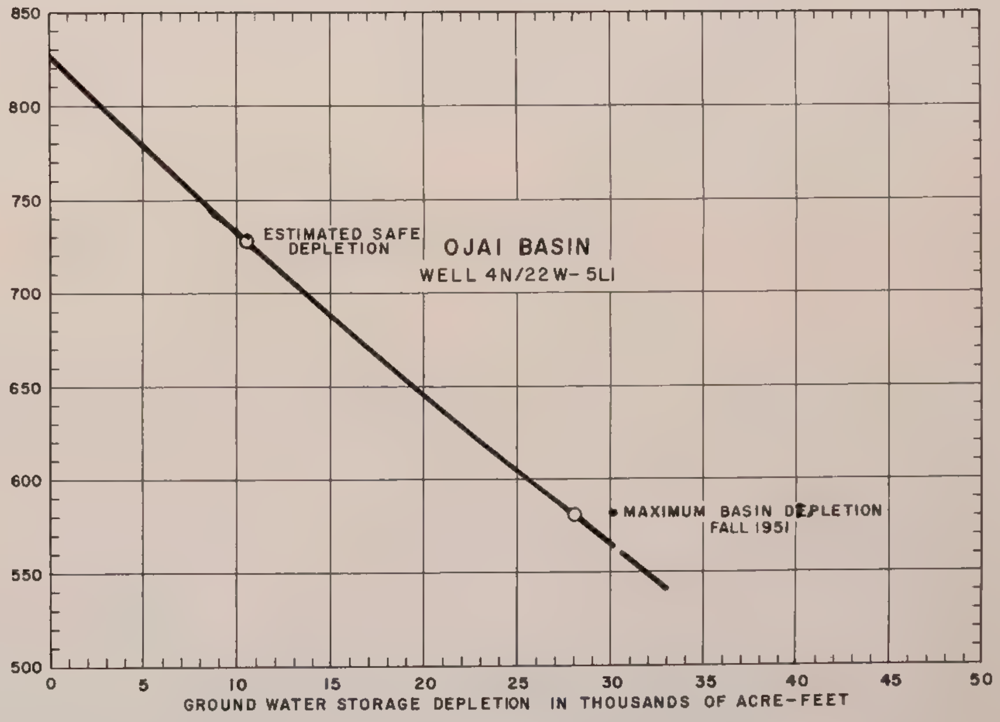
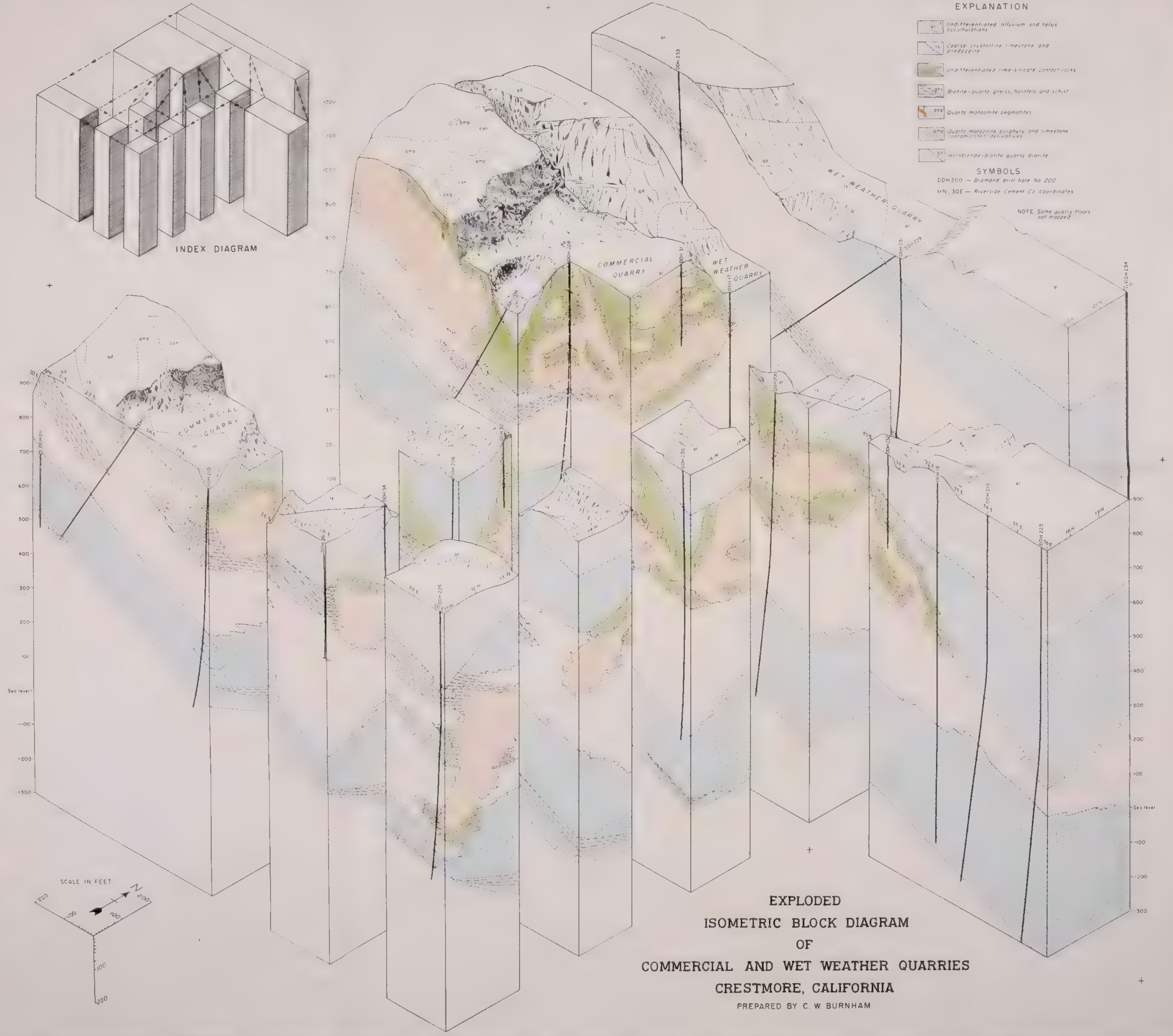
BULL. 170 CHAPT. 6
CONTRIB. 3 PLATE 10








INDEX DIAGRAM
EXPLANATION
al Undifferentiated alluvium and talus accumulations
ls Coarse crystalline limestone and predazzite
con Undifferentiated lime-silicate contact rocks
ghs Biotite-quartz gneiss, hornfels and schist
peg Quartz monzonite pegmatites
qmp Quartz monzonite porphyry and limestone contaminated derivatives
qd Hornblende-biotite quartz diorite
SYMBOLS
DDH 200 — Diamond drill hole No 200
11N, 30E — Riverside Cement Co coordinates
NOTE Some quarry floors not mapped
COMMERCIAL QUARRY
WET WEATHER QUARRY
DDH 233
DDH 228
DDH 231
DDH 217
DDH 229
DDH 234
DDH 211
DDH 210
DDH 34
DDH 236
DDH 226
DDH 230
DDH 232
DDH 219
DDH 223
Sea level
SCALE IN FEET
N
200
100
100
200

EXPLODED
ISOMETRIC BLOCK DIAGRAM
OF
COMMERCIAL AND WET WEATHER QUARRIES
CRESTMORE, CALIFORNIA
PREPARED BY C. W. BURNHAM

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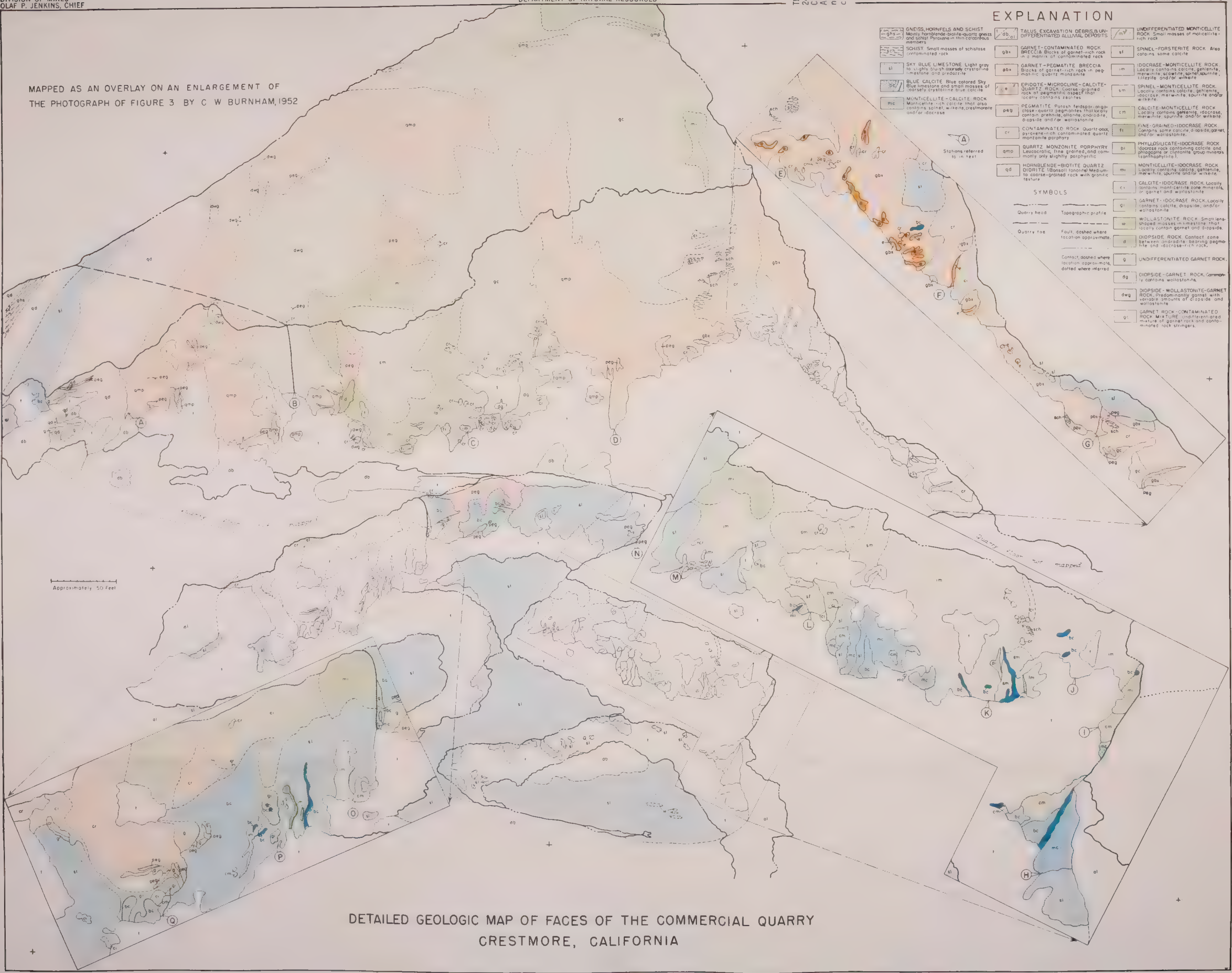
MAPPED AS AN OVERLAY ON AN ENLARGEMENT OF THE PHOTOGRAPH OF FIGURE 3 BY C. W. BURNHAM, 1952
Approximately 50 Feet
Quarry floor not mapped
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q

EXPLANATION

ghs	GNEISS, HORNFELS AND SCHIST Mainly hornblende-biotite-quartz gneiss and schist. Pyroxene in thin calcareous members
sch	SCHIST. Small masses of schistose contaminated rock
sl	SKY BLUE LIMESTONE. Light gray to slightly bluish coarsely crystalline limestone and predazzite
bc	BLUE CALCITE. Blue colored Sky Blue limestone and small masses of coarsely crystalline blue calcite
mc	MONTICELLITE-CALCITE ROCK. Monticellite-rich calcite that also contains spinel, wilkeite, crestmoreite and/or idocrase
db / al	TALUS, EXCAVATION DEBRIS & UNDIFFERENTIATED ALLUVIAL DEPOSITS
gbx	GARNET-CONTAMINATED ROCK BRECCIA. Blocks of garnet-rich rock in a matrix of contaminated rock
pbx	GARNET-PEGMATITE BRECCIA. Blocks of garnet-rich rock in pegmatitic quartz monzonite
e	EPIDOTE-MICROCLINE-CALCITE-QUARTZ ROCK. Coarse-grained rock of pegmatitic aspect that locally contains zeolites
peg	PEGMATITE. Potash feldspar-oligoclase-quartz pegmatites that locally contain prehnite, allanite, andradite, diopside and/or wollastonite
cr	CONTAMINATED ROCK. Quartz-poor, pyroxene-rich contaminated quartz monzonite porphyry
qmp	QUARTZ MONZONITE PORPHYRY. Leucocratic, fine grained, and commonly only slightly porphyritic
qd	HORNBLENDE-BIOTITE QUARTZ DIORITE (Bonsall tonolite). Medium- to coarse-grained rock with granitic texture
m	UNDIFFERENTIATED MONTICELLITE ROCK. Small masses of moticellite-rich rock
sf	SPINEL-FORSTERITE ROCK. Also contains some calcite
im	IDOCRASE-MONTICELLITE ROCK. Locally contains calcite, gehlenite, merwinite, scawtite, spinel, spurrite, tilleyite and/or wilkeite
sm	SPINEL-MONTICELLITE ROCK. Locally contains calcite, gehlenite, idocrase, merwinite, spurrite and/or wilkeite.
cm	CALCITE-MONTICELLITE ROCK. Locally contains gehlenite, idocrase, merwinite, spurrite and/or wilkeite.
fi	FINE-GRAINED-IDOCRASE ROCK. Contains some calcite, diopside, garnet, and/or wollastonite.
pi	PHYLLOSILICATE-IDOCRASE ROCK. Idocrase rock containing calcite and phlogopite or clintonite group minerals (xanthophyllite).
mi	MONTICELLITE-IDOCRASE ROCK. Locally contains calcite, gehlenite, merwinite, spurrite and/or wilkeite.
ci	CALCITE-IDOCRASE ROCK. Locally contains monticellite zone minerals, or garnet and wollastonite
gi	GARNET-IDOCRASE ROCK. Locally contains calcite, diopside, and/or wollastonite
w	WOLLASTONITE ROCK. Small lens-shaped masses in limestone that locally contain garnet and diopside.
d	DIOPSIDE ROCK. Contact zone between andradite-bearing pegmatite and idocrase-rich rock.
g	UNDIFFERENTIATED GARNET ROCK.
dg	DIOPSIDE-GARNET ROCK. Commonly contains wollastonite.
dwg	DIOPSIDE-WOLLASTONITE-GARNET ROCK. Predominantly garnet with variable amounts of diopside and wollastonite
gc	GARNET ROCK-CONTAMINATED ROCK MIXTURE. Undifferentiated mixture of garnet rock and contaminated rock stringers.

Ⓐ Stations referred to in text

SYMBOLS

Quarry head

Topographic profile

Quarry toe

Fault, dashed where location approximate.

Contact, dashed where location approximate, dotted where inferred

DETAILED GEOLOGIC MAP OF FACES OF THE COMMERCIAL QUARRY
CRESTMORE, CALIFORNIA

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STATE OF CALIFORNIA
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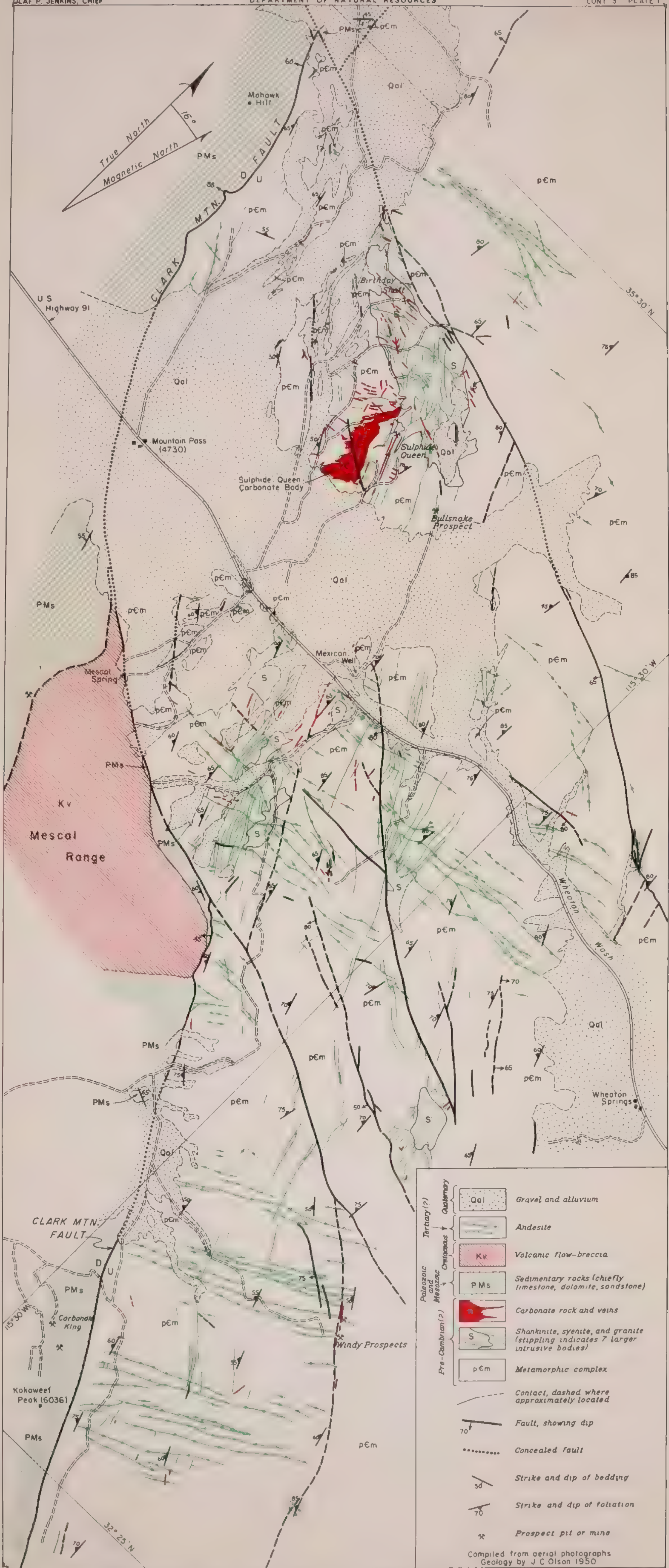
BULL 170 CHAP VIII
CONT 3 PLATE I

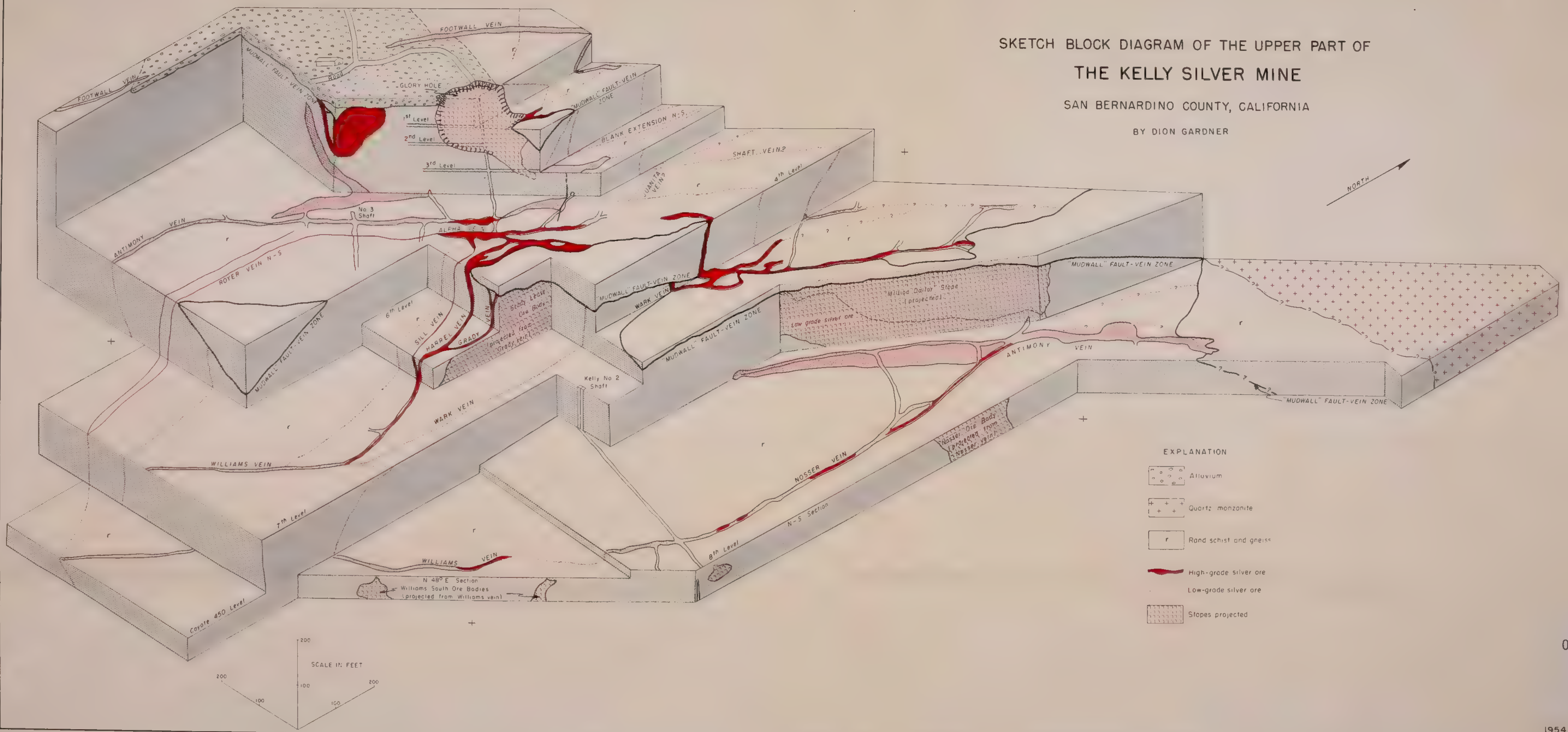


GENERALIZED GEOLOGIC MAP OF MOUNTAIN PASS DISTRICT
SAN BERNARDINO COUNTY, CALIFORNIA

SKETCH BLOCK DIAGRAM OF THE UPPER PART OF
THE KELLY SILVER MINE

SAN BERNARDINO COUNTY, CALIFORNIA

BY DION GARDNER



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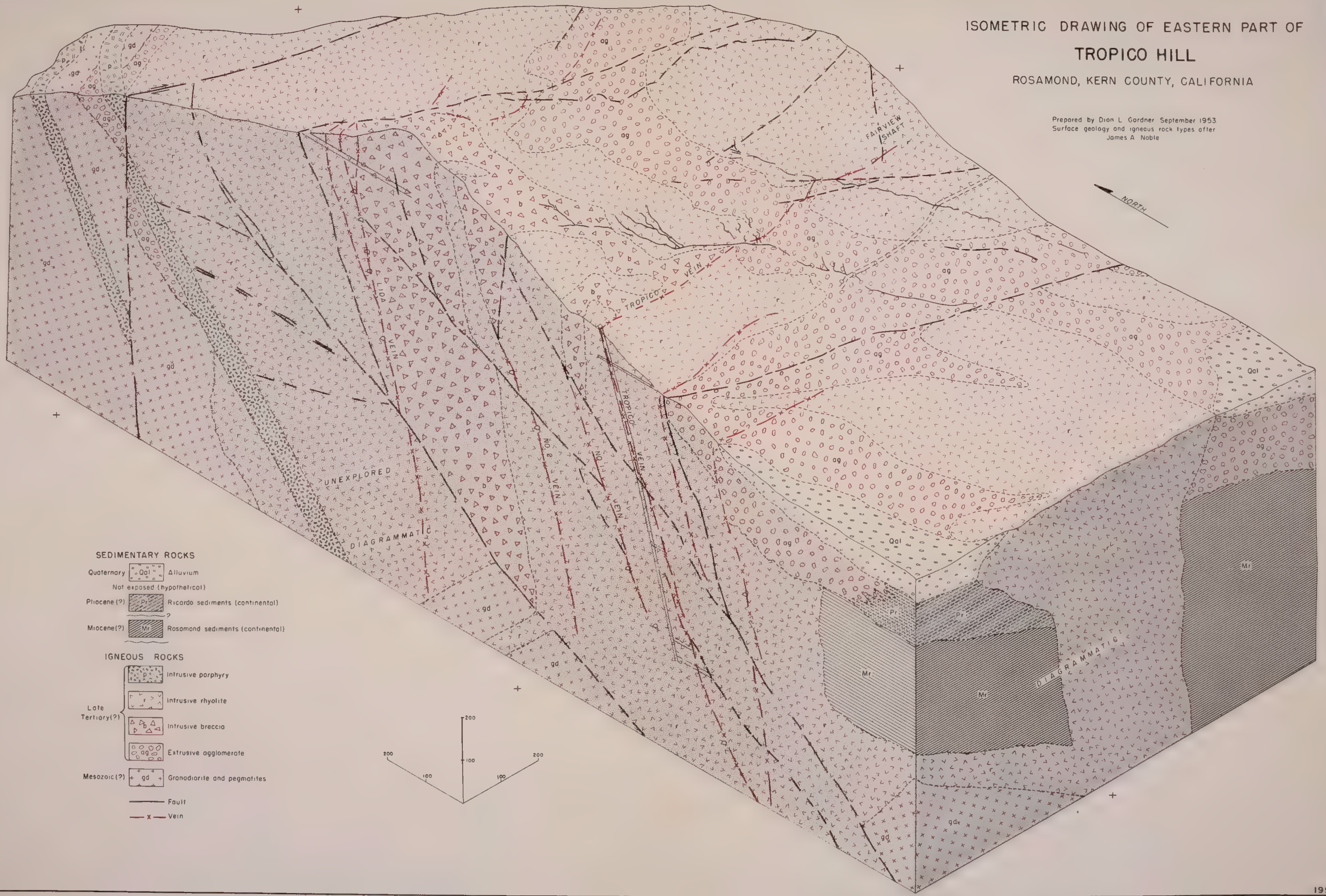
ISOMETRIC DRAWING OF EASTERN PART OF
TROPICO HILL
ROSAMOND, KERN COUNTY, CALIFORNIA

Prepared by Dion L Gardner September 1953
Surface geology and igneous rock types after
James A Noble



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GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER IX

OIL AND GAS

1954

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5. Geologic guide for the northern part of the Peninsular Range province, southern California

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San Francisco | Bulletin 170 | September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER IX

OIL AND GAS

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Editorial Note:

CHAPTER NINE outlines the principal features of occurrence of oil and gas in southern California, and summarizes much of the geologic information that has led to discovery and production of these important commodities. The phenomenal growth of the petroleum industry in California, which now furnishes about one-sixth of the total domestic output, has raised it to a position second only to agriculture in economic importance within the State. This growth has been founded in large part upon the astonishing increases in local demands for petroleum products, and in equally large part upon the discoveries of remarkably rich accumulations of oil and gas that commonly occupy reservoirs of great vertical extent as compared with their projected surface areas.

A very high percentage of the petroleum occurs in strata that were laid down during Cenozoic time in several well defined basins of deposition. Understanding and prediction of its distribution involve considerations of stratigraphy and structure on a wide range of scales, and many of the features and relations discussed in Chapters III and IV, for example, have become known through the efforts of geologists engaged in the search for new reserves of petroleum. Thus the increasingly imaginative application of an increasing variety of exploration techniques has contributed generously to the current state of knowledge of southern California geology, and especially so with respect to relations in the subsurface.

The four papers in this chapter discuss the more general aspects of southern California's petroleum industry, as well as geologic factors that are related to it. In addition, the significant geologic features of twenty selected oil and gas fields are shown on individual map sheets, chiefly by means of surface and subsurface maps, structure sections, and a variety of diagrams. These map sheets appear in a separate pocket, along with several other map sheets of areas known to contain petroleum-bearing rocks.

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1. HISTORY OF OIL EXPLORATION AND DISCOVERY IN CALIFORNIA*

By Harold W. Hoots † and Ted L. Bear †

In 1859 this country's first commercial oil production, from Drake's well on Oil Creek in western Pennsylvania, generated a search for petroleum that extended rapidly westward to Ohio, Kansas, Oklahoma, Texas, and California. During the 93 years since that sensational first discovery, this search by pioneering prospectors and, later, by trained scientists led to the discovery of an estimated 78 billion barrels of oil in the United States. Of this amount an estimated total of 13.3 billion barrels has been found in California.

Although the search for oil in California extended to almost all areas of even remote possibilities, the commercial oilfields of today are strikingly concentrated in six isolated and relatively small districts (fig. 1) that have a combined area equal to only about 5 percent of the entire State.

Prospecting Near Seepages. The first prospectors of the early sixties were attracted to oil seeps in the more accessible coastal areas of Humboldt County, Half Moon Bay and Santa Cruz, Ojai and Sulphur Mountain, the Santa Clara Valley east of Ventura, and the northern border of the Los Angeles basin. They discovered some oil in all of these places, but, according to Pemberton (1943, p. 3), cumulative production from these small discoveries prior to the end of 1875 amounted to only 175,000 barrels. Later, the prospecting activities were extended to areas of seepages along the east and west borders of the San Joaquin Valley.

During the next 32 years these prospectors discovered many small fields and several large ones, including McKittrick, Midway-Sunset, East and West Coalinga, Kern River, Brea Canyon, Whittier, Salt Lake, Orcutt, and Lompoc. All of these fields, containing a total of 2.5 billion barrels of oil (fig. 2), were discovered by drilling near seepages. They include several of our most important stratigraphic traps and fault traps, and other traps that are principally anticlinal.

Geological Search for Anticlines and Fault Traps. Geological knowledge acquired in universities was applied in a small way to oil exploration in California as early as the period 1900-05. Although random prospecting continued effectively to supplement the search for oil, it is clear that consideration of surface geology was beginning to dominate the discovery record in 1908, when the prospecting of several prominent anticlines led to discovery of the West Coyote, Cat Canyon, and Buena Vista Hills fields. By 1916, study of surface and subsurface geology was generally accepted in the industry as a valuable aid in the search for oil. The discovery rate began to climb sharply at this time, and there followed a 14-year period of unusual success, during which were discovered almost all of the remaining known major fields of California in which anticlinal or fault structure is reflected at the surface. Surface work, supplemented by subsurface studies during this period, accounted for many large and small fields of the San Joaquin basin and the Ventura-Santa Barbara district, and for all of the remaining known major fields of the Los Angeles basin except Wilmington.

The 28-year period of geological exploration from 1908 to 1935, inclusive, saw the discovery of an estimated total of 7.6 billion barrels of oil (fig. 3). The average annual rate for this period was 270 million barrels, as compared to 77 million barrels for the preceding period of prospecting.

The Reflection Seismograph and Stratigraphic Geology. In 1936 the work of a reflection seismograph party operated by the Shell Oil Company led to the discovery of the Ten Section oilfield by showing the existence and position of an anticline that lies entirely concealed beneath the thick alluvial fill of the San Joaquin Valley. The Buena Vista dry gas field was discovered by the Ohio Oil Company 2 years earlier, as a result of the work of a G.S.I. reflection seismograph party under the direction of Henry Salvatori, Party Chief. The structure responsible for this gas accumulation in Pliocene rocks is the Paloma anticline. Additional seismograph surveys of this area during the period 1937-39 led to the development in 1939 of prolific oil production from deeper sands of Miocene age.

The Ten Section discovery established the fact that large anticlinal structures and thick Miocene oil sands lie hidden beneath the valley floor, and that these anticlines could be found by means of the reflection seismograph. Thus began a new era in the search for oil fields in California, and there followed during the period 1936-39 the discovery of the Greeley field by the Standard Oil Company of California; the Canal, Strand, and South Coles Levee fields by the Ohio Oil Company; the Rio Bravo field by the Union Oil Company; the North Coles Levee field by the Richfield Oil Corporation; and the Paloma field by The Texas Company and the Western Gulf Oil Company. The reflection seismograph also has been responsible for the discovery of almost all commercial gas fields of the Sacramento Valley.

Systematic seismograph surveys were continued by major companies, and are still in progress throughout the San Joaquin basin.

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† Consulting Geologist, Los Angeles.

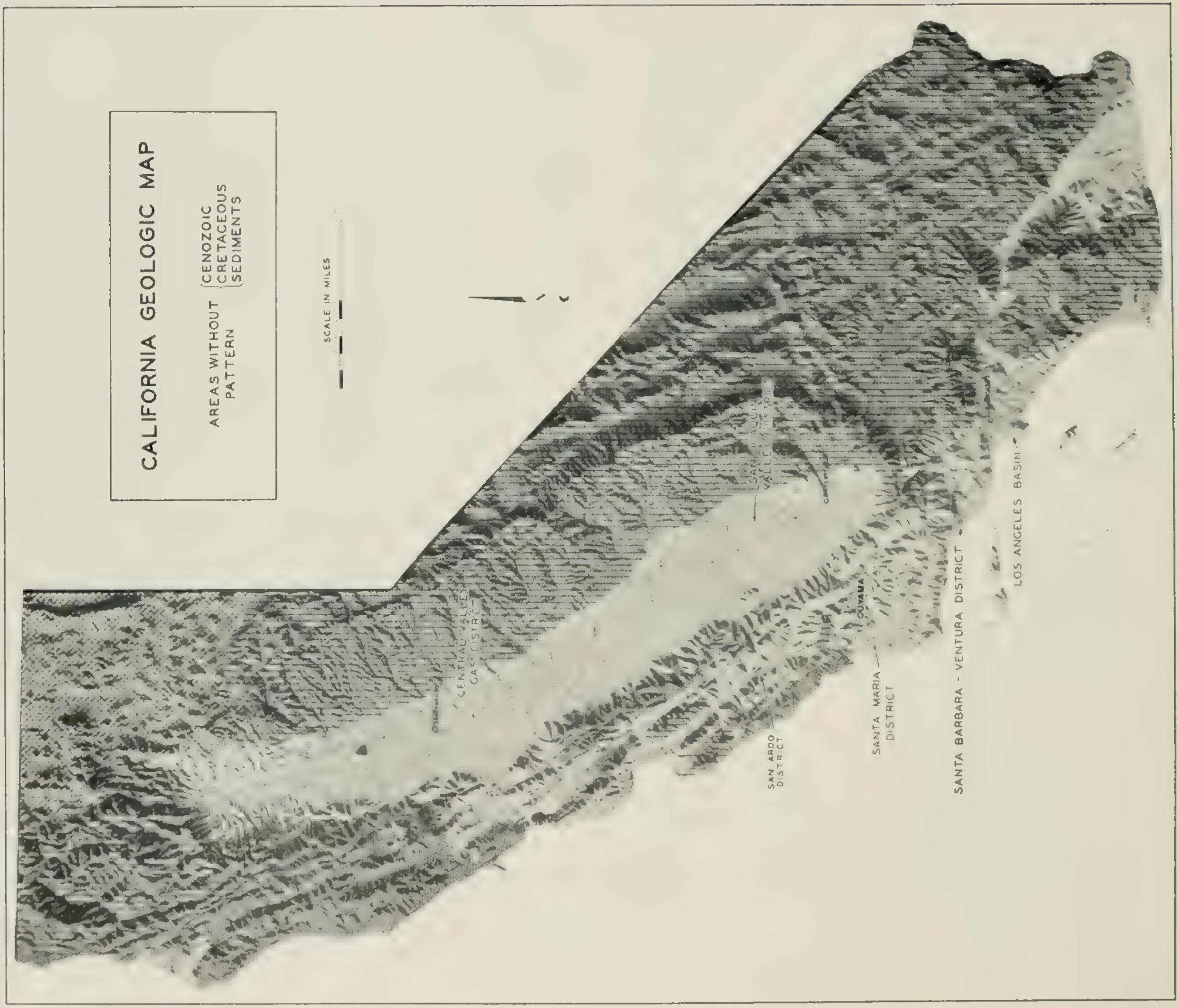

FIGURE 1. Relief map of California showing locations of oil districts.

but only a few additional oil fields of relatively minor importance have been found by this method during more recent years. These include three fields discovered in 1941: Helm by the General Petroleum Corporation, Raisin City by the Shell Oil Company, and Riverdale by the Amerada Petroleum Corporation. During the 17 years since 1936, when search with the seismograph began, a total of 3.2 billion barrels of oil was discovered, of which 1.8 billion barrels is credited to seismograph surveys. Represented in this total are the Wilmington field of the Los Angeles basin, the only major oil field outside the San Joaquin basin discovered solely by means of the seismograph, and the Santa Maria Valley and the East Coalinga Eocene fields, which were discovered as a result of subsurface stratigraphy geology. The average annual rate of discovery for this 14-year period was 188 million barrels.

The Santa Maria Valley field, discovered by the Union Oil Company in 1936, was the first major stratigraphic-trap oilfield found in California since geologists first recognized the importance of such features and began searching for them. This discovery thus brought to the attention of operators the importance of a new phase of geological exploration which, in contrast to the long-established surface and subsurface methods of mapping anticlines and faults, was largely dependent upon studies of regional and local stratigraphy, structure, and paleogeography. This latest geological approach to the search for oil is herein called stratigraphic geology.

The value of such studies in the Mid-Continent region had been emphasized earlier by the discovery of the East Texas oilfield, and it seemed apparent to many investigators that such studies should be particularly applicable to conditions in California. Their reasoning was based chiefly upon two major factors: (1) rapid lateral changes in facies, along with complex structures, are common characteristics of the California Tertiary section, and (2) an enormous quantity of pertinent structural and stratigraphic information is available from rock outcrops and thousands of well records. The recognized requirements for effective work in stratigraphic geology were detailed field mapping, extensive and systematic sample collecting and foraminiferal studies, and much subsurface work.

This new approach to the search for oil yielded excellent results with the discovery of the East Coalinga Eocene (Gatchell) field in 1938, the Antelope Hills field in 1942, the Pleasant Valley field in 1943, the Cymric and Santiago fields in 1943, and the Guijarral Hills field in 1948.

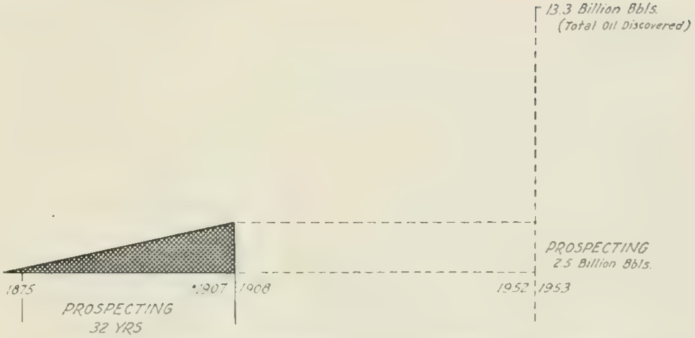

FIGURE 2. Estimated discoveries of oil in California by early prospecting.

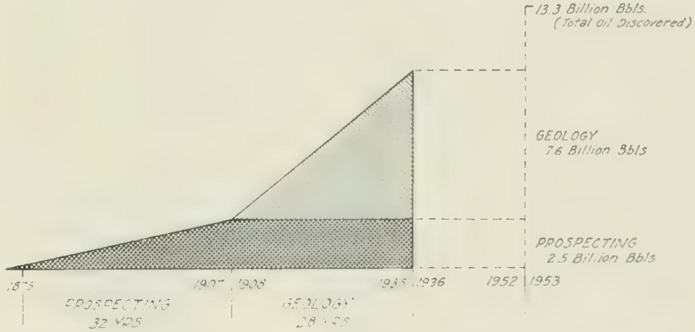

FIGURE 3. Estimated discoveries of oil in California by early prospecting and geologic search for anticlines and fault traps.

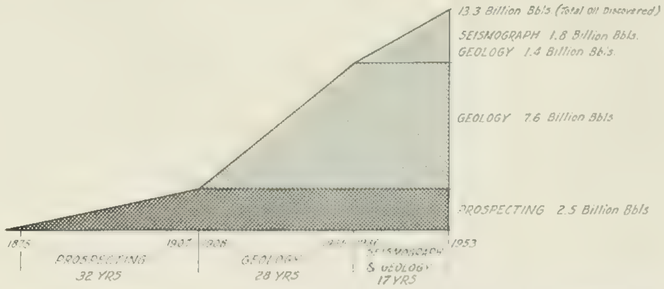

FIGURE 4. Estimated total discoveries of oil in California by all methods prior to 1953.

Discovery of Two New Districts. The year 1948 was an important one in the history of exploration for oil in California. The discoveries of sizeable reserves in two new districts, Cuyama Valley and Salinas Valley, made dramatic news, principally because they were almost

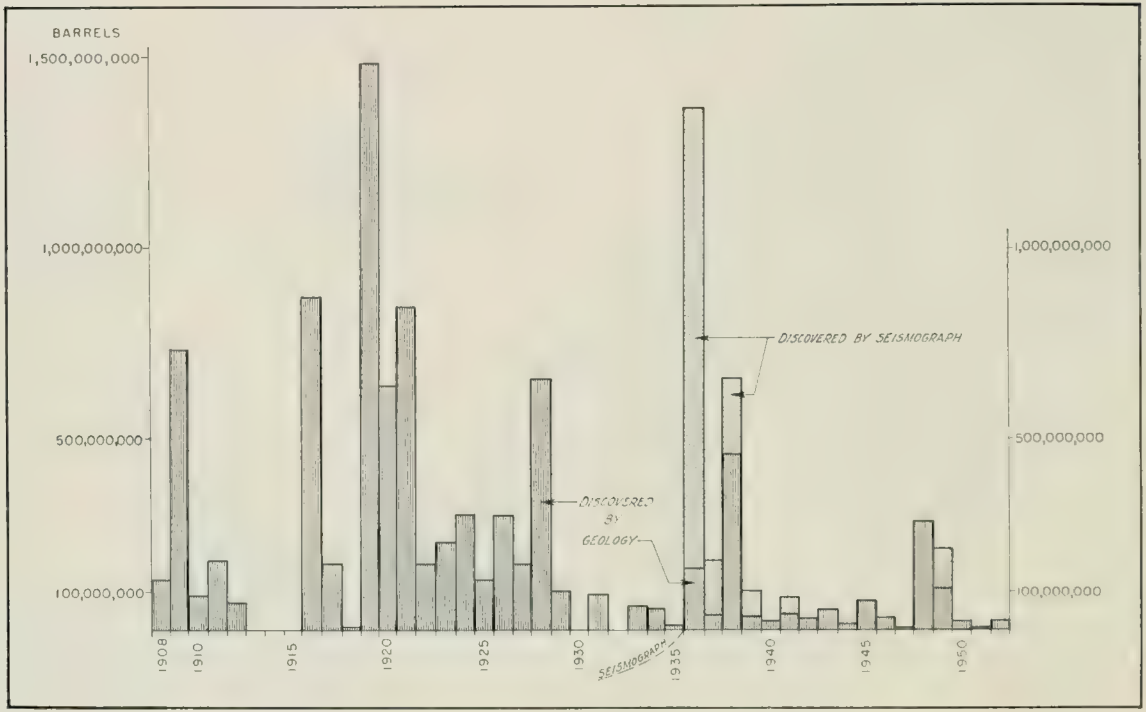

FIGURE 5. Oil discovery record for California by individual years.

wholly unexpected by at least 95 percent of the investigators in the oil industry. These were the first discoveries of new oil districts since the days of early prospecting. To a large extent they were the result of the application of stratigraphic thinking to available surface and subsurface data, despite the fact that the individual oil traps in these districts have proved to be structural, rather than stratigraphic, in nature. The discovery wells of the individual fields in these new districts are located within areas of pronounced convergence of some part of the Miocene marine section.

Within 2 years these new districts contributed half a billion barrels to California's oil reserve; given time for more thorough exploration, their ultimate potentialities should prove to be appreciably greater.

The Discovery Record by Years. The chart of figure 4 may give the erroneous impression that the rate of oil discovery has followed a fairly smooth curve from the beginning. Figure 5, however, shows the discovery record by individual years and reveals that the rate of discovery has fluctuated irregularly between wide limits. This chart allocates all of the oil in any one field to the year of discovery of that field. For example, all of the oil in the eight zones of the Santa Fe Springs field is allocated to the year in which this field was discovered regardless of the number of years required to establish the presence of all eight zones. This chart, therefore, shows the results of discovery of new fields—the results of exploratory geology. It is based on the premise that the primary responsibility of an exploration geologist is to discover new fields, and that all zones in a given new field will be discovered in due time without his further attention.

The discovery chart of figure 5 starts with 1908, the approximate beginning of the period of geological search for anticlines and fault traps. The erratic nature of the discovery rate is particularly striking; some years were rich in the quantity of newly discovered oil, whereas others were lean or were without discovery of any sort. Geology did a remarkable job in discovering 6 billion barrels of oil during the 13-year period 1916-28. This represents an annual discovery rate of 460 million barrels, a rate that was about double the average annual consumption for that period. The 7-year depression period 1929-35 was extremely lean, but following this were 4 comparatively rich years, 1936-39. These in turn were followed by an 8-year period, 1940-47, of consistently meager discoveries. This discouraging period of lean years was similar to that of 1929-35. It was brought to a close in 1948 and 1949 by the discovery of the Guijarral Hills field, two fields in Cuyama Valley, and the San Ardo field of Salinas Valley. The low totals of field discoveries during the following 3 years, 1950-52 inclusive, suggest the beginning of another period of lean years.

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2. ORIGIN, MIGRATION, AND TRAPPING OF OIL IN SOUTHERN CALIFORNIA

By Frank S. Parker *

The subjects of origin, migration, and trapping of oil are perhaps the most controversial ones in petroleum geology. The many theories, particularly those concerning origin and migration, have not been susceptible to proof in the field or laboratory; and exceptions, or seeming exceptions, can be found for every theory yet propounded. Publications referring to these subjects are so numerous as to constitute an entire field of special study, and the writer does not pretend to have read and digested more than the most pertinent of these papers. A rather extensive consideration of the historical and current theories was presented some years ago by Hoots (1941), and the present writer will review only the more recent plausible theories and factual data. The references given at the end of this paper do not constitute a bibliography of the subject, and the reader is referred to De Golyer and Vance (1944), ZoBell (1947), Russell (1951), and to Landes (1951) for more complete coverage.

The writer will assume it to be essentially proved that oil had its origin from organic matter deposited with the fine-grained sediments, the source rocks, and that it migrated from these sediments into carrier or reservoir rocks and eventually accumulated in traps where it now is found.

The least controversial of the three title subjects is accumulation, or, more precisely, the physical description of the traps in which oil is found. Many of the traps have been thoroughly explored and some can be dated as to time at which they became effective. For these traps, at least, migration and origin can be considered on a sound basis.

Oil in southern California is found in simple domed anticlines, in faulted anticlines or noses, in fault traps on homoclines, in stratigraphic traps resulting from buttressing, lensing, truncation, or decrease in permeability, and in fractures in otherwise impermeable rocks. Some traps appear to have been formed through sealing of outcrops by tar, and probably some accumulations are formed because of the relatively low water table in an open reservoir. Traps involving limestone and dolomite porosity, reefs, and salt domes do not occur in southern California, and thus far no accumulation can be ascribed solely to hydraulic factors.

The classification of traps has been an interesting exercise for many writers (see for example, Sanders, 1943; Wilhelm, 1945; Brod, 1945). The present author submits, in the accompanying tabulation, a system of classification based on factors governing accumulation.

Table 1. Factors governing accumulation of oil and gas.

- STRUCTURAL FACTORS
  - ANTICLINE
    - Quaquaversal dip.
  - FAULT
    - Curving fault or intersecting faults on homocline.
  - FRACTURING
    - Formation of reservoir within impermeable rock by shattering and dilatancy.
  - COMBINATIONS OF THE ABOVE
- LITHOLOGIC FACTORS
  - DEPOSITIONAL FEATURES. Lensing, buttressing, gradation into tight sediments, channel sands, bars, beaches, reefs.
  - EROSIONAL FEATURES. Truncation, weathered regolith, cavernous weathering, dolomitization.
  - CEMENTATION. Filling of pores with cementing material, including tar. Kaolinization and swelling of feldspars and clays.
  - COMBINATIONS OF THE ABOVE
- FLUID FACTORS
  - DYNAMIC. Hydraulic action trapping oil in structure not closed under static conditions.
  - STATIC. Low fluid level permitting accumulation in reservoirs open at outcrop.
- COMBINATIONS. Any combination of conditions of the above three general categories.

Within a single field different pools may result from a number of different types of traps. Nearly all factors may be modified by one or more other factors, but it generally is possible to assign one, or sometimes two, factors as the principal cause of accumulation in a given pool, the other factors serving only to modify the extent, shape, or production characteristics of the reservoir. A few examples may serve to illustrate this.

The Ventura Avenue field is an anticline with quaquaversal dip, but the actual productive area of some pools on the north limb of this fold has been extended down dip by faulting. The Del Valle field is on an anticline that plunges eastward and presumably would not produce in the present developed area were it not for a combination of fault or lithologic closure or both. The Placerita field (Willis, 1952; Oakeshott, this bulletin) is monoclinal, possibly slightly synclinal, and closure is provided by intersecting faults, probably abetted by some quirk of fluid dynamics. The Brea-Olinda field is a faulted homocline in which lateral closure is accomplished by slight bowing of the contours into the fault. In the Dominguez anticline (Graves, this bulletin) the Pliocene pools are on the structural high, but the Miocene pools lie west of faults at lower structural positions.

The writer has classified 253 pools in the various fields that lie within southern California and that are listed by the Conservation

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Committee (1953). Some of the listed pools were so designated for engineering purposes, and do not constitute separate accumulations; on the other hand several accumulations in some fields are grouped as a single pool. Certain variations from the list, therefore, have been made by the writer.

Structural factors alone are the control in 200 pools. Quaquaversal dip governs accumulation in 108 of these, fault closure in 32, a combination of faulting and folding in 52, and a combination of folding and fracturing in 8.

Lithologic factors are the primary control in 15 pools, of which eight are closed by lensing or buttressing, two are sealed on eroded edges of reservoirs, and five are closed by cementation with tar.

No pool has been demonstrated to be dependent primarily on dynamic fluid conditions, although tilted water tables affect the outlines of some pools. Three pools exist because low fluid level has failed to expel the oil from the open outcrop.

Anticlines or noses combined with depositional features account for 22 pools, and, with cementation, for two additional pools. Faults combine with depositional features to form eight other pools.

One pool each can be ascribed to combinations of faulting and a dynamic fluid condition, to static fluid level on a fold nose, and to static fluid level in a fracture zone.

Reasons for the accumulation of four pools were undetermined.

Within the area studied some 4,996 million barrels of oil was produced to the end of 1952, and of this 3,951 million was obtained from simple or only slightly modified anticlinal traps, 331 million from simple or slightly modified fault closures, and 574 million from structures closed by folding and faulting in almost equal degree. The remaining 140 million barrels was derived from other features, in large part from depositional closures on folds.

The classification of traps here used takes into account only their present physical conditions. Conceivably, at least in some instances, the oil may have first accumulated in its present location because of other factors, and subsequent folding, faulting, fluid movements, or cementation, without having made significant changes in the location of the trap, might at present appear to have controlled the accumulation. In some fields, however, the present trapping factors seem to have been the only ones that could have operated effectively; thus, if the time at which these factors became effective can be established, the earliest time when migration of the trapped oil took place can be established, also.

At Santa Fe Springs (Winter, 1941), beds in the vertical range from the top of the upper Pliocene to a horizon at least 1,000 feet into the upper Miocene are conformable and show no appreciable thinning over the fold. This dates the folding and forming of the trap as post-upper Pliocene. The fill-up and areal extent of the Hathaway pool, of Miocene age, are greater than those of the Bell pool, which is one of the largest Pliocene pools and lies nearly 3,500 feet higher. As the age of the trap is dated, the accumulation must have taken place after the close of upper Pliocene time, and the sources must have been adequate to fill both the younger and older reservoir rocks.

At Dominguez and Rosecrans there is some evidence of fold growth through much of Pliocene time. The Pliocene pools are high on closed domes, but the Miocene pools, for the most part, lie off the crestal position against faults that formed after deposition of at least some beds of lower Pliocene age. There appear to be no fluid-dynamic factors to account for the sweeping away of oil from Miocene beds in the crestal position that would not apply equally well to the Pliocene beds. One is left with the inference that the Miocene oil migrated to its present position at a time no earlier than lower Pliocene.

In the Oak Ridge fields, such as South Mountain and Shiells Canyon, the folding and thrusting can be no older than lower Pliocene, and for the most part must have been early Pleistocene in age (fig. 1). The oil is found in Oligocene Sespe beds of continental origin, and in Eocene marine beds. The source of the oil is subject to some controversy (Baddley, this bulletin), but Bailey (1947) believes the Eocene rocks to be the source. Although this source may be disputed, the age of accumulation is indicated as post-lower Pliocene, and perhaps even as late as Pleistocene.

Woodring (1951) presents evidence to show that oil accumulated in the "later Miocene-older Pliocene" Sisquoc beds and, in escaping and burning at the outcrop, calcined masses of Sisquoc shale. Pebbles formed from these calcined shales are found in Orcutt sand of post-middle Pleistocene age, but not in Careaga beds of late Pliocene age—a strong suggestion that the oil accumulation was a late-occurring phenomenon.

McNaughton (1953) has made a strong case for migration into reservoirs of basement rocks due to opening-up of fractures (dilatancy) after deposition of the adjacent source rocks. With this concept is an unexpressed implication that the source rocks must be sufficiently lithified to resist flowage into these fractures.

In the Santa Maria district the presence of water-worn pebbles of Monterey shale in late Pliocene beds proves the lithification of the Monterey by late Pliocene time. The folding of the late Pliocene beds to a degree almost equal to that of the reservoir beds and presumed source rocks of Monterey age in some of the producing structures suggests that the oil was accumulated after compaction and lithification of the source rocks. These examples, and many others, imply

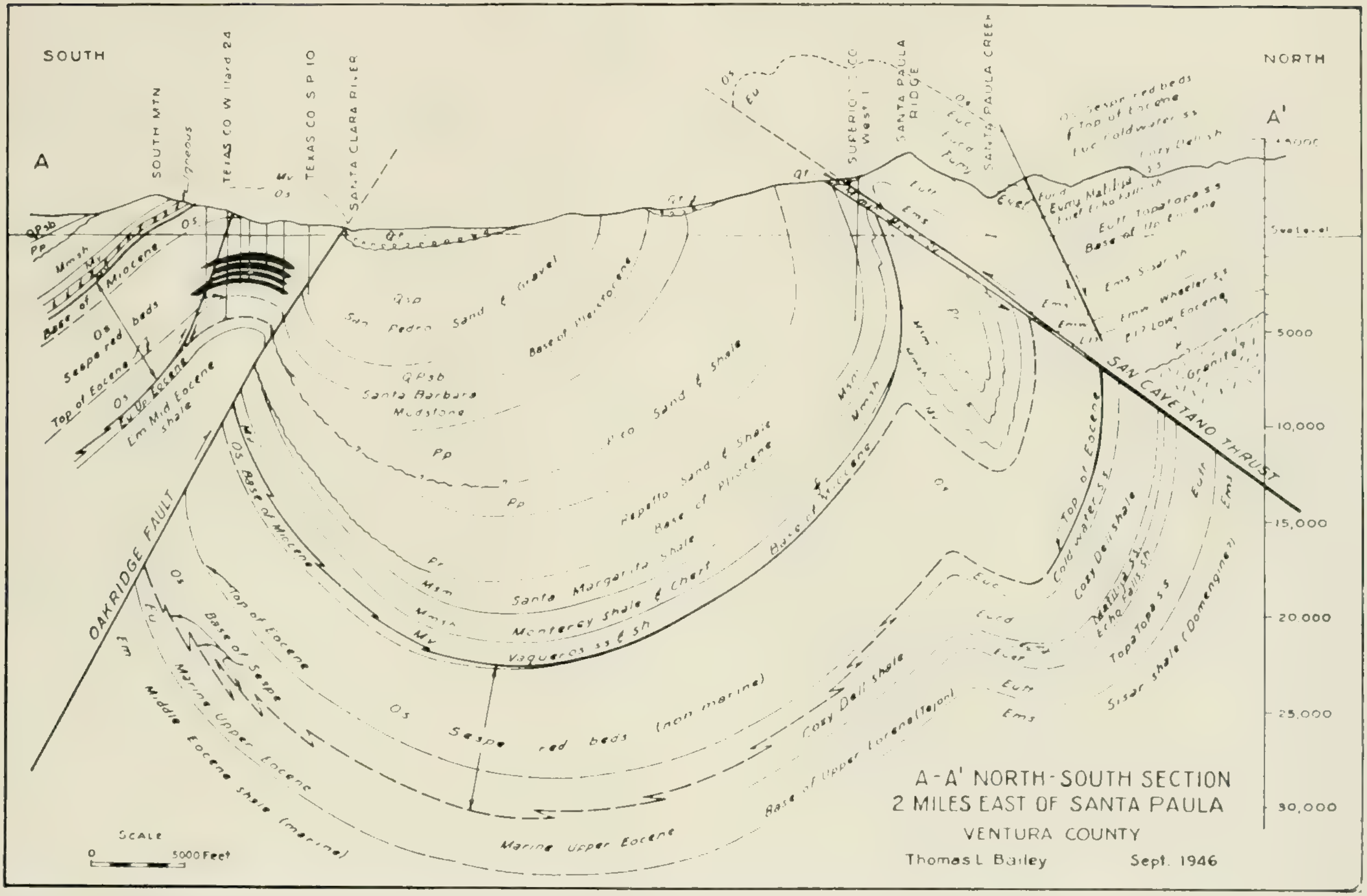

FIGURE 1. Cross section of Oakridge and Santa Clara Valley. Conformity of pre-upper Pliocene beds dates the effectiveness of the South Mountain trap as upper Pliocene or later. *After Bailey, 1947.*

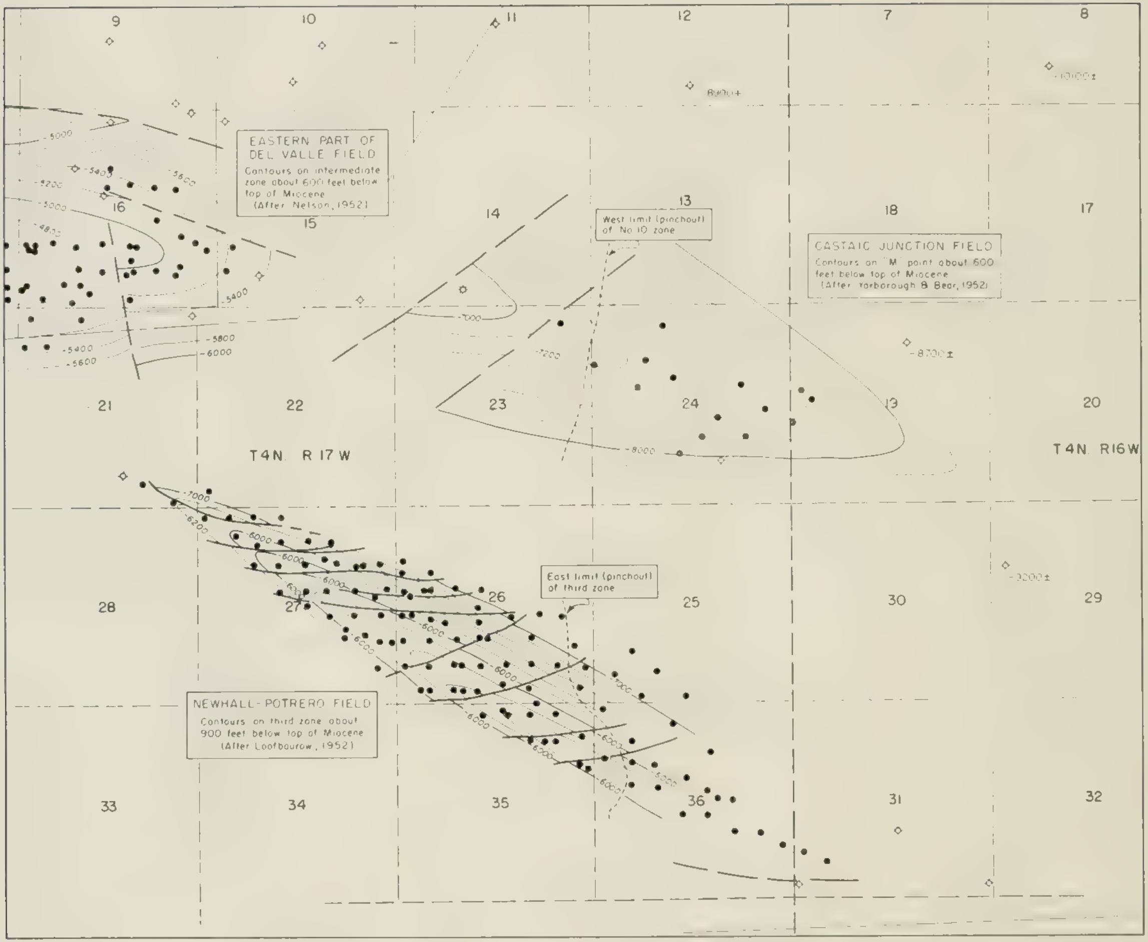
9
10
11
12
7
8
8900±
-10100±
EASTERN PART OF
DEL VALLE FIELD
Contours on intermediate zone about 600 feet below top of Miocene
(After Nelson, 1952)
-5000
-5400
-5600
-5200
-4800
-5800
-6000
16
15
14
13
18
17
West limit (pinchout) of No 10 zone
CASTAIC JUNCTION FIELD
Contours on "M" point about 600 feet below top of Miocene
(After Yarborough & Bear, 1952)
-7000
-7200
-8000
-8700±
21
22
23
24
19
20
T4N. R17W
T4N. R16W
-6200
East limit (pinchout) of third zone
28
27
26
25
30
29
-9200±
NEWHALL-POTRERO FIELD
Contours on third zone about 900 feet below top of Miocene
(After Loofbourow, 1952)
33
34
35
36
31
32

FIGURE 2. Del Valle, Castaic Junction, and Newhall-Potrero fields. Contours in fields, as well as points in selected wildcat wells, are on roughly equivalent horizons. Note accumulation against eastward pinchout in the Newhall-Potrero field, and against westward pinchout in the Castaic Junction field. Much of the Del Valle field is controlled also by westward pinchout. Faults marked "f" control, or at least greatly modify, accumulation in one or more pools. The low point of the basin in this vicinity probably lies near the east quarter corner of sec. 18, T. 4 N., R. 16 W. *Data compiled from sources noted, with modifications and additions by writer.*

that accumulation took place long after deposition and most of the compaction of the rocks.

The possible explanations of this relation are: (1) Oil may be formed early but is retained, at least in part, within the source beds until some later action expels it; or (2) oil is generated from the organic material long after the source beds are compacted and lithified; or (3) oil originates early but is held in some other reservoir trap, which in turn is spilled into the present traps; or (4) oil migrates so slowly in carrier beds that some will be caught, even though the trap is formed very long after the oil first enters the carrier bed; or (5) oil originates in younger beds as they are deposited over folds, and migrates downward through thousands of feet of sediments.

In considering the first alternative, various writers (ZoBell, 1927; Knebel, 1946; Mead, 1949; Weeks, 1952; Emery and Rittenberg, 1952; Oakwood, 1949) have shown that oil and gas are, or can be, formed in recent sediments. Smith (1952) has noted the presence of hydrocarbons of crude-oil nature in cores obtained from recent sediments in the Gulf of Mexico. These substances were rather uniformly distributed through 106 feet of core, and amounted to 0.031 percent of the dried weight of the sediment, or to about four barrels of oil per acre foot of sediment in natural condition. Intensive research is being pursued currently in this field.

As the sediment is compacted (Hedberg, 1936; Hoots, 1941, pp. 259-260; Hubbert, 1953, pp. 1974-1979) the capillary effect of preferential wetting of most mineral grains by water would cause a greater tendency to expel oil than to expel water into the coarser sediments, and it is supposed that only a small part of the original fluid hydrocarbons could be retained. Nevertheless, in California at least, there are large volumes of fine-grained rocks in the sedimentary basins as compared to the total volume of oil in known fields, and if an appreciable percentage of fluid hydrocarbons remains after initial compaction, further compaction or some other agency might still expel a large volume of oil at some later time. Certainly many cores of compacted shale show bubbles of gas and spots of oil, even in areas where cores of reservoir-type sands do not contain oil or even traces of oil. If the Meyer shale at Santa Fe Springs is taken as an example, a shale body 165 feet thick and underlying some 8 square miles may be considered to lie within the drainage area of the structure. Trask and Patnode (1942, p. 455) show that cores from this interval in Union Oil Co. "Howard" 8 contain 0.04 percent to 1.21 percent by weight of bitumen soluble in carbon tetrachloride. The average of seven samples is 0.25 percent. Taken as 0.60 percent by volume this would amount to more than 33 million barrels of soluble bitumen now remaining in this body of shale after its compaction and moderate lithification. This, of course, is oil that has not reached the productive reservoirs, but it might do so in the future. Unfortunately, bitumen analyses of this shale body in adjacent non-productive areas are not available for comparison, but analyses of similar sediments outside of producing fields show bitumen percentages of the same order of magnitude.

Although the evidence that compacted shales can retain large volumes of bitumen does not prove that this material is all crude oil or that it always was present in the liquid state, it does show the possibility that substantial amounts of liquid oil could have been retained since the time of deposition.

In considering the second thesis, investigators (Sheppard and Whitehead, 1946; Pratt, 1934; Cox, 1946; Grim, 1947) have shown experimentally or theoretically that fluid hydrocarbons can be formed from organic solids by distillation under both low or high temperatures and low or high pressures. Fluid hydrocarbons also can be formed by radioactivity, hydrogenation, or the action of bacteria. An objection, as cited by Brooks (1936), to any theory introducing temperatures above 140° C. for the origin of oil from organic solids or gases by chemical reaction is the common presence in crude oils of chlorophyl porphyrins. These substances are quickly destroyed at temperatures above 140° C., and could not be synthesized under subsurface conditions. Brooks therefore contends that, as derivation of oil from solids by destructive distillation or by cracking requires temperatures in excess of 200° C., only some other origin at a low temperature is possible. Since Brooks published his studies, deeper drilling has resulted in production of oil from reservoirs more than 15,000 feet beneath the surface, with reservoir temperatures of more than 150° C. recorded at Wasco field in the San Joaquin Valley and at West Poison Spider field in Wyoming. In both fields the trap was formed after burial to approximately the depth of the present pools, and at least in these cases, either Brooks' tenets are unsound or the oil must have been formed early and retained in the source beds until it was released to the reservoirs after folding.

The third possibility involves the spilling of a previous reservoir into a later trap, but such a field as Castaic Junction (Yarborough and Bear, 1952) is incompatible with this theory. The oil at Castaic Junction is found in lenses or fault traps in upper Miocene beds that lie far basinward down a plunging nose that was folded and faulted in upper Pliocene time (fig. 2). It is nearly impossible to conceive of a reservoir in a position to spill oil into this very deep structure. Also, if it were supposed that spilling took place from a former accumulation to the east, the supposition would not account for accumulation in the Third zone of the Newhall-Potrero field, which is closed by an eastward pinchout. Almost equally difficult to explain

Table 2. Oil fields of southern California classified as to type of trap.

FIELD	POOL	REMARKS
1. Control by Structural Factors		
A. ANTICLINE		
SOUTH CUYAMA	Johnson Homan Hibberd	Faulting increases effective closure
ELWOOD	Vaqueros Sespe	Two domes
GOLETA	Sespe	
SAN MIGUELITO	First Grubb Second Grubb Third Grubb	
VENTURA AVENUE	Fourteen of sixteen pools	Two pools are equally due to faulting
BARDSDALE	Sespe Eocene	
DE WITT CANYON		Abandoned
PICO CANYON		
RICE CANYON		
TOWSLEY CANYON		
WILEY CANYON		Abandoned
OAK CANYON	Four A, Four B, Five A, Six A-B, Seven, Eight A-B	
LION MOUNTAIN	Sespe Eocene	Abandoned
HOPPER CANYON		
SHIELLS CANYON		
SOUTH MOUNTAIN		Extended by faulting
TORREY CANYON	Shallow	
COYOTE EAST	Hualde Anaheim	
COYOTE WEST	Top Main Ninety-nine Emery	
DOMINGUEZ	One, Two, Three, Four, and Five	
HUNTINGTON BEACH	A 37 A 66 Jones Main	Faulting and permeability are additional minor factors
INGLEWOOD	Vickers Rindge Rubel Moynier	
LONG BEACH	Alamitos Brown Deep De Soto	
LAWNDALE	Upper	
MONTEBELLO	First, Second, Third, Fifth, Sixth, Seventh, and Eighth	Pliocene and Miocene folds have different axes
PLAYA DEL REY	Pliocene	
RICHFIELD	Chapman Kraemer	
ROSECRANS	Athens Upper Athens Lower Athens O'Dea Maxwell Hoge Main Zinns South Zinns	
1. Control by Structural Factors—Continued		
A. ANTICLINE—Continued		
SEAL BEACH	San Gabriel Bixby Selover Wasom McGrath Lane	Faulting has altered shape of field, but structure is primarily an anticline
WILMINGTON	Tar Ranger Terminal U. P. Ford	Numerous pools in different fault blocks; faults probably have extended field beyond normal dip closure
BELMONT		
BEVERLY HILLS		
KRAEMER		
EAST LOS ANGELES	Vail U. P. 3 U. P. 1	May have some lithologic and fault control
SANTA FE SPRINGS	Foix Bell Meyer Nordstrom Buckbee O'Connell Clark Hathaway	
B. FAULT		
RUSSELL RANCH	Sloan Dibblee Colgrove Russell "15-9" Norris Griggs-Dibblee	
MORALES CANYON	Clayton	
COAL OIL POINT	Vaqueros	Abandoned
SANTA BARBARA	Vaqueros	
ALISO CANYON	Aliso Aliso West Porter Del Aliso Sesnon Faulted Sesnon Eocene	
SISAR-SILVERTHREAD		
SULPHUR MOUNTAIN NORTH		
HOLSER CANYON		
PLACERITA	Juanita	
TIMBER CANYON		
BREA-OLINDA	Brea Olinda Tonner	
NEWPORT MESA		
NEWPORT WEST	Main Aldrich B Aldrich C Kidson	
PLAYA DEL REY		
WHITTIER		
LA MIRADA		
LEFFINGWELL		Lensing may have an influence
LOS ANGELES		

Table 2. Oil fields of southern California classified as to type of trap.—continued

FIELD	POOL	REMARKS
1. Control by Structural Factors—Continued		
C. FAULTED ANTICLINE		
SOUTH CUYAMA	Cox	
CAPITAN	Vaqueros	
	Erburu	
	Covarrubias	
	Coldwater	
LA GOLETA GAS	Vaqueros	
SUMMERLAND		
RINCON	Main	
	Oakgrove	
	Padre Canyon	
VENTURA AVENUE	D5 North	
	D6 North	
	D7	
ALISO CANYON	Mission	
CASTAIC JUNCTION	Zone 15	
	Zone 21 East	
	Zone 21 West	
DEL VALLE	Bering	
	Lincoln	
NEWHALL POTRERO	Second	
MODELO		
TEMESCAL		
TAPO SOUTH		
TORREY CANYON	Deep	
WEST MOUNTAIN		
COYOTE EAST	Miocene A	
	Stern	
DOMINGUEZ	Six, Seven, Eight, "D"	
HUNTINGTON BEACH	Tar Bolsa	
	Fault Zone	
	Ashton	
INGLEWOOD	Sentous	
LONG BEACH	Northwest	
	Wardlow	
MONTEBELLO	Fourth, Cruz	
	Nutt	
POTRERO	East, West	
	Inglewood City	
ROSECRANS	Howard Zinns	
	Howard Seven	
	Howard Eight	
	Main Seven	
	Bank Seven and Eight	
	Main Eight	
	South O'Dea	
	South Eight	
SANSINENA		
BUENA PARK		Some lithologic control
SALT LAKE		
TURNBULL		
NORTH WHITTIER HEIGHTS		
D. ANTICLINE AND FRACTURING		
ELWOOD	Temblor Shale	Fractured shale
SULPHUR MOUNTAIN		Fractured shale
EL SEGUNDO	Schist	
NEWPORT	Beach	Fractured shale
PLAYA DEL REY	Schist	
WILMINGTON	Schist	
PUENTE HILLS		Fractured shale
HYPERION	Schist	
2. Control by Lithologic Factors		
A. DEPOSITIONAL		
MORALES CANYON	Government "18"	Buttress
TAYLOR CANYON	Bishop	Buttress
OAK CANYON	One A	Lensing
WELDON CANYON		
TAR CREEK		Lenses
ANAHEIM		Buttress
B. EROSIONAL		
OXNARD		Unconformity
NEWHALL TOWNSITE		Unconformity
C. CEMENTATION		
ADAMS CANYON		Tar seal
ALISO OLD		Tar seal
SALT MARSH		Tar seal
SANTA PAULA CANYON		Tar seal
WHEELER CANYON		Tar seal
3. Control by Fluid Factors		
A. DYNAMIC		
NONE IDENTIFIED		
B. STATIC		
CONEJO		Oil in basalt vesicles at water table
FOUR FORKS		Outcrop open
FOOT-OF-HILL		Outcrop open
4. Combination of Factors Controlling Structure and Lithology		
A. ANTICLINE AND DEPOSITIONAL		
CASTAIC JUNCTION	Zone Ten	Siltout
DEL VALLE	Sepulveda	Pinchout
	Vasquez "13"	Pinchout
	Vasquez-Videgain	Pinchout
	Vasquez "14"	Pinchout
SIMI		Lenses
HASLEY CANYON		Pinchout
NEWHALL POTRERO	First	
	Third	
	Sixth	
	Seventh	
	Ninth	Factors uncertain, meagre data
OAK CANYON	Three A-B	
ALONDRA		Basal conglomerate lens
EL SEGUNDO	Miocene	Basal conglomerate lens
	Gas	Lenses
COYOTE WEST	McNally	
HUNTINGTON BEACH	Tar Zone	
LAWNDALE	Lower	Basal conglomerate lens
RICHFIELD	Breen	
TORRANCE	Tar-Ranger	
	Main	
	Del Amo	
WILMINGTON	"237"	
	Conglomerate	

Table 2. Oil fields of southern California classified as to type of trap.—continued

FIELD	POOL	REMARKS
4. Combination of Factors Controlling Structure and Lithology—Continued		
B. ANTICLINE AND CEMENTATION		
LITTLE SESPE		
NEWHALL-POTRERO	Fifth	
C. FAULT AND DEPOSITIONAL		
DEL VALLE	NLF 3-1 Kinler	
HONOR RANCHO	Sterling Rancho Wayside	
RAMONA	Black Kern	
NEWPORT	Anaheim Sugar	
YORBA LINDA	Shell Smith	

FIELD	POOL	REMARKS
5. Control by Structure and Fluid		
A. FAULT AND DYNAMIC		
PLACERITA	Old	
B. ANTICLINE AND STATIC		
TOPATOPA	Vaqueros Sespe	
C. FRACTURES AND STATIC		
TIP TOP	Miocene shale	Fractured shale porosity
D. UNDETERMINED		
MONTALVO		
LAS LLAJAS		
HORSE-MEADOWS		
TAPO SOUTH		

by means of the spilling theory is the Ventura Avenue field, which is a central-basin anticline that was formed in early Pleistocene time and yields oil from beds as old as basal Pliocene with no evidence of a possible former reservoir in a position to spill into this structure. In the writer's opinion, the spilling theory could be accepted for only a few highly unusual occurrences.

The fourth concept, that of continuing slow migration or essentially "transient storage" in carrier beds, appears not to be susceptible to actual proof or disproof. The writer believes, however, that to satisfy this concept there should be more evidence of migrating oil just below the capping shale of reservoirs near oil fields. Oil commonly is noted at such positions, but much more commonly the reservoir sand is entirely gray. The presence of oil streaks may be due as well to some micro-trap caused by minor faulting or lensing. The slow-migration theory also is weak in explaining the oil that has equal or greater fill-up in the older reservoirs, where a much longer period of time should have enabled the "transient" oil to get out of "storage" before the trap was formed.

As to the fifth thesis, that of downward migration, the presence of intermediate waters precludes downward movement, except possibly by molecular diffusion (Russell, 1951, p. 226). If this agency is sufficient to account for oil in the deepest reservoirs, the same agency would have long ago exhausted the shallow reservoirs by upward diffusion, unless they are being filled at such rates that outside wells should have found substantial amounts of migrating oil.

Theorists (Walters, 1948) have cited the work of Leverett (1939), which shows zero permeability to oil of a sand completely saturated with water, as evidence that oil could not have migrated as a liquid. However, evidence provided by tilted water tables and hydraulic-controlled traps (Green and Ziemer, 1953; Hubbert, 1953, pp. 2012-26) with sharp oil-water contacts, shows that oil can be swept out of sand entirely unless we make the absurd assumption that the hydraulic gradient has remained precisely the same since the accumulation started. Furthermore, the existence of pools of late Pliocene low-gravity oil that is undersaturated with gas scarcely is compatible with concepts of non-liquid accumulation.

In summary, the following conclusions can be drawn:

Oil accumulates in traps possibly before and during, but certainly also after, compaction and lithification of the associated sediments.

Oil, by some process or in some manner, can migrate distances of many miles.

Oil can migrate as a liquid crude material, at least for short distances, leaving essentially no trace of its passage in the sands.

Oil could have been generated contemporaneously with deposition, or at any later time, but some substantial part must have been retained in the source beds, even after compaction and moderate lithification of these beds.

Criteria for identification of source beds have not been established, but inference suggests that a high content of organic material may not be necessary in such beds.

A region of permeable reservoir rock and good traps should not be condemned without adequate testing merely because of apparent lack of source beds.

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3. OIL AND GAS PRODUCTION IN CALIFORNIA

By Frank B. Carter *

Historical Review. The first drilling for oil in California probably dates from 1861, when a prospect well was drilled on the Davis Ranch in Humboldt County in the northern part of the State. The first recorded production of crude oil in California was from a well drilled by the Union Mattole Oil Company in 1865, near the Mattole River in Humboldt County. The depth of this pioneer oil well is reported to have been 260 feet. Others followed the first producer, but the Humboldt County wells could not sustain a commercial rate of production for any length of time, and the operators soon lost interest in the area.

At about the same date, oil-minded people in California were becoming interested in the possibilities of obtaining production from other parts of the State, particularly from Santa Clara, San Mateo, and Santa Cruz Counties in the north, and from Santa Barbara, Ventura, Kern, and Los Angeles Counties in the south. Wells were drilled in a number of these counties during 1865 and 1866. Attention was attracted to several areas by extensive oil seeps and surface exposures of bituminous residue. Little was known, in those early days, of the geologic conditions that control oil accumulation, and most of the drilling was done in the vicinity of the oil seeps and the outcrops of oil-bearing sands.

During this first period of activity in California, several wells were drilled in the Ojai-Sulphur Mountain district of Ventura County. A well capable of producing about 20 barrels of oil daily was completed in 1866 by the California Petroleum Company under the direction of Thomas Bard. This appears to have been the first commercial oil well to be completed in southern California, and it probably yielded the best production obtained anywhere in California up to that time.

Following California's first oil boom in 1865 and 1866, there was little activity for several years, owing primarily to the lack of market demand for petroleum products. Both the early refineries built by Stanford Brothers at San Francisco and the plants constructed in Santa Cruz and Santa Clara Counties to treat surface exposures of bituminous material were, for the most part, shut down.

In the early 1870's, attention was attracted to the Newhall area, in the northwestern part of Los Angeles County. Wells were drilled in Pico Canyon, near Newhall, and in 1876 the California Star Oil Works Company completed Pico No. 4 for a daily production of 30 barrels from a depth of 300 feet. This well was the forerunner of the second oil boom in California. Interest became centered in two principal areas, Newhall in Los Angeles County, and Moody Gulch in Santa Clara County, and in addition a few wells were drilled in other areas. Production from the Moody Gulch field soon declined rapidly, but the Newhall area continued to develop.

In 1879 the Pacific Coast Oil Company was formed by a merger of several smaller companies operating in California, including the California Star which was then drilling in Pico Canyon. The famous

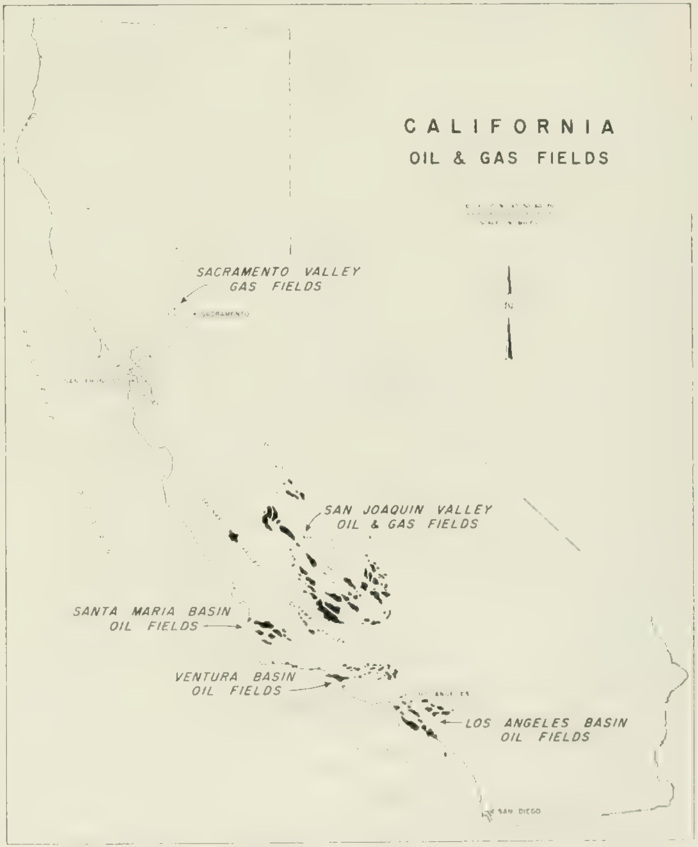
CALIFORNIA
OIL & GAS FIELDS
SACRAMENTO VALLEY GAS FIELDS
SACRAMENTO
SAN JOAQUIN VALLEY OIL & GAS FIELDS
SANTA MARIA BASIN OIL FIELDS
VENTURA BASIN OIL FIELDS
LOS ANGELES BASIN OIL FIELDS
SAN DIEGO

Figure 1. Index map of oil and gas fields of California.

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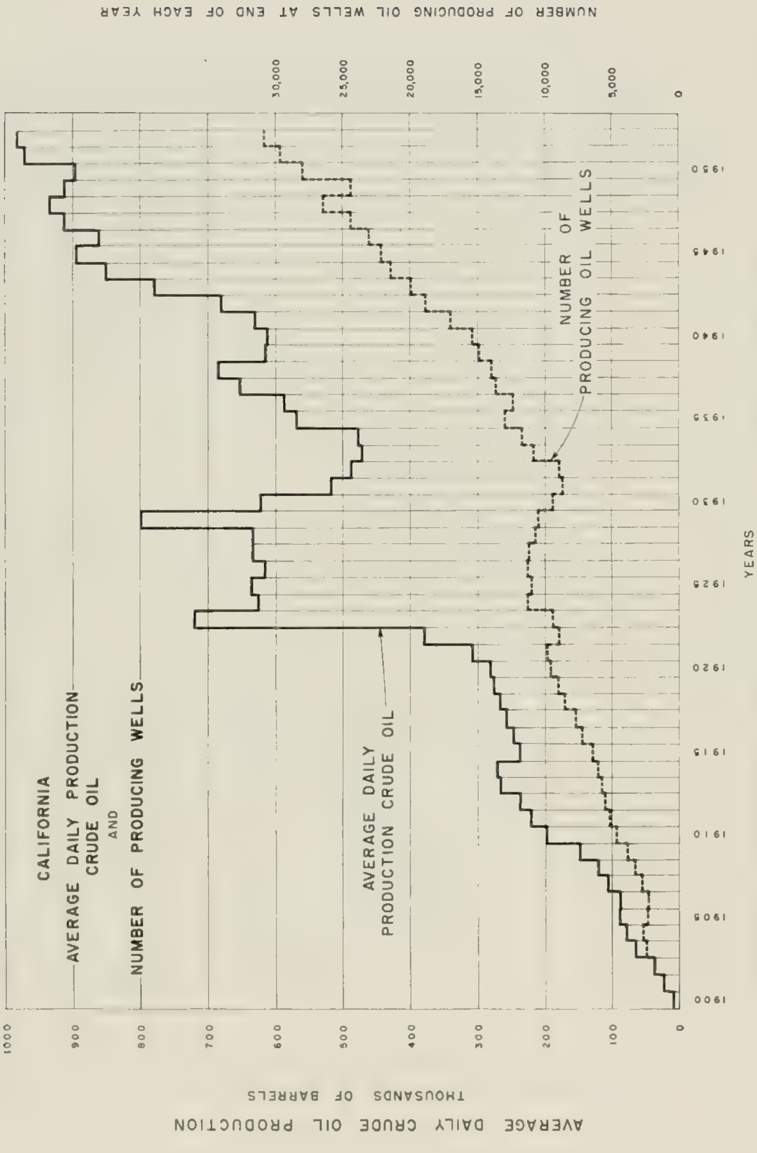

FIGURE 2. Graph showing average daily oil production in California, 1900 to 1952 inclusive.

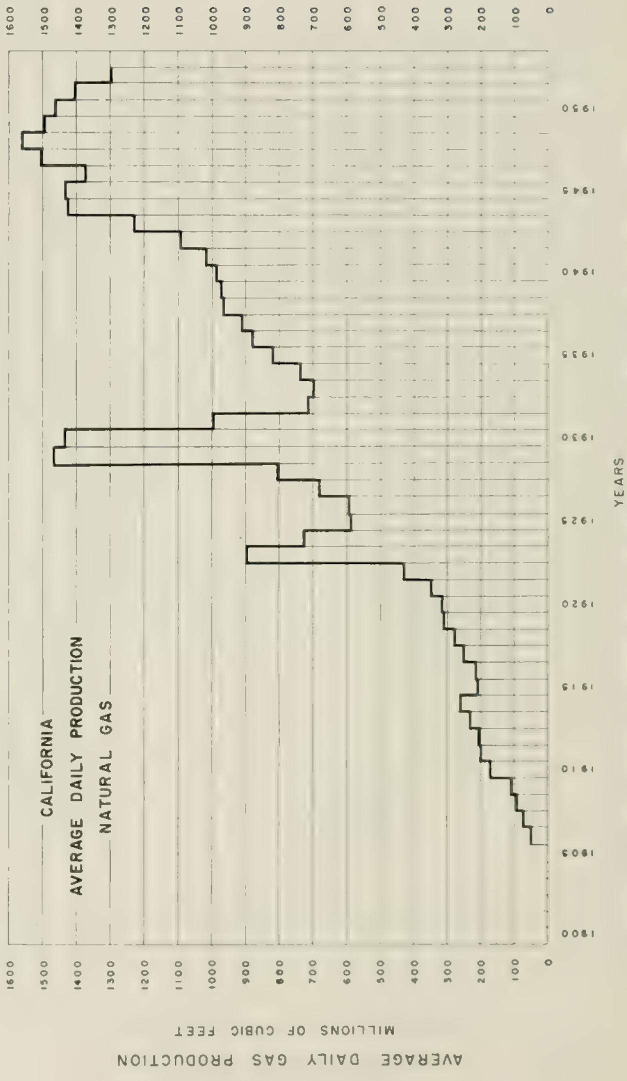

FIGURE 3. Graph showing average daily gas production in California, 1906 to 1952 inclusive.

Pico No. 4 well was deepened to 600 feet, and the production increased to an unprecedented 150 barrels daily. This led to the construction of the first oil pipe line in California. Five miles of 2-inch line were laid from Pico Canyon to a newly constructed refinery on the Southern Pacific Railroad near Newhall. This oil line, and the first refinery in southern California, were in operation at the end of 1879. It is worthy of note that the oil industry has taken steps to preserve this refinery as a record of its early history in California.

The decade from 1880 to 1890 witnessed further development of the fields in the Newhall area and in Ventura County to the west. The introduction of steam power greatly speeded drilling operations. During this period, oil was discovered in the Los Angeles basin, when production was obtained in the Puente Hills near Whittier.

The first water-borne tankers, with a capacity of 6,500 barrels, were constructed in 1888 to transport oil from Ventura to San Francisco. Prior to this time, all oil movements to San Francisco had been by rail.

In 1890, the Pacific Coast Oil Company, with properties in Pico Canyon and elsewhere, became affiliated with the Standard Oil Company of California. The property in Pico Canyon still produces, and is still operated by Standard under the name of "Pacific Coast". During 1890, also, the Union Oil Company of California was formed by the merger of the properties of Hardison and Stewart, two oil pioneers in California, and several other smaller concerns.

Two years later, in 1892, the first big well in California was completed, when the Union Oil Company brought in No. 28 in the Adams Canyon field, a few miles northwest of the town of Santa Paula in Ventura County. It flowed at an initial rate of 1,500 barrels daily, and aroused a great deal of interest in the industry.

A year later, in 1893, E. L. Doheny was responsible for the discovery of oil within the city of Los Angeles. This resulted in the first town-lot drilling boom in California, and the field rapidly developed into the largest producer in the State. Between 1896 and 1899 the Coalinga, Kern River, and McKittrick fields in the San Joaquin Valley were opened.

At the turn of the century approximately 2,400 oil companies were incorporated in the State of California, and about half of these actually were engaged in drilling operations. During the year 1900, the daily average production rose to nearly 12,000 barrels, and in 1905 it reached 91,500 barrels. This latter output was from 2,450 producing wells. The oil industry in California was well on its way, but it is doubtful whether anyone at that time visualized the tremendous developments that were to take place during the next half century.

During the first decade of the Twentieth Century, production from the California fields increased nearly seventeen-fold. Within this period, the famous gushers in the Orcutt field near Santa Maria were brought in, some of them yielding as much as 12,000 barrels of oil per day. In 1910, while the Midway-Sunset field was being developed, the greatest gusher that the United States has ever known came in. This was the now famous Lakeview No. 1, near the town of Maricopa in Kern County. This well flowed out of control for 544 days from a depth of 2,225 feet and reached an estimated peak daily output of approximately 68,000 barrels a few days after coming in. Much of the oil was caught in open ditches and behind hastily constructed dams and it is conservatively estimated that 8¼ million barrels of oil * were produced by this phenomenal well in only about 18 months' time. The gravity of the oil was 11° API. The well is reported to have been still flowing about 18,000 barrels daily when it suddenly sanded up and stopped producing. Although redrilled, it never again yielded much oil. No other wells of this nature ever have been completed in this area to date.

Between 1910 and 1920, the Ventura Avenue, Belridge, Montebello, and several other fields were discovered, and production and development continued on an upward trend. Production in 1920 was about twice that in 1910, in contrast with the seventeen-fold increase during the previous decade. During this period World War I demonstrated the vital importance of oil in military and naval operations.

The decade 1920 to 1930 witnessed the discovery of practically all of the important fields in the Los Angeles basin, with the exception of Wilmington. The development of all these fields caused the State's production to climb to a daily average of 720,200 barrels for the year 1923, and the output rate reached a peak of 850,000 barrels per day in August of that year. This flood of oil from such prolific fields as Santa Fe Springs, Long Beach, and Huntington Beach brought about a sharp reduction in the price of crude oil and a consequent reduction in crude oil output. A plan of voluntary curtailment, which was followed by most California operators, went into effect in 1929 with the creation of the State Oil Umpires Office.† The production record established in 1923 was surpassed only once (in 1929) during the next 20 years, and finally was exceeded in 1944 as a result of unprecedented demands during World War II.

The business depression of the early thirties virtually halted all exploratory drilling effort in California, and no new fields were found for several years. Production declined to a daily average of 471,260 barrels during 1933, the lowest rate in 10 years. Except for a few minor leveling-off periods, production since 1933 has been on a

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* From records filed with the California State Mining Bureau by the Union Oil Company, dated February 15, 1914.

† This later became the presently existing Conservation Committee of California Oil Producers.

Table 1. Pertinent data on principal oil fields of California.

Principal fields	Year discovered	Type of accumulation	Type reservoir rock	A. P. I. gravity range	Average or range of completion depths	Age of producing formations	Proved acres to 1/1/53	Recovery bbls. acre to 1/1/53	Total production to 1/1/53 M. bbls.	1952 production in barrels per day
Ventura Basin										
Alsо Canyon	1938	Faulted anticline	Sands	22°-53°	5300′- 7850′	Pliocene and Miocene	1,000	16,124	16,124	6,633
Capitan	1929	Anticlinal	Sands	16°-43°	1400′- 2700′	Miocene, Oligocene, Eocene	275	56,196	15,454	1,562
Castaic Junction	1950	Faulted anticline	Sands	20°-45°	10400′-11900′	Miocene	550	1,516	834	1,443
Del Valle-Ramona	1940	Anticlinal	Sands	31°-34°	6200′- 7000′	Pliocene and Miocene	1,300	20,483	26,628	6,874
Elwood	1928	Anticlinal	Sands	32°-40°	3100′- 4400′	Miocene and Oligocene	675	135,919	91,745	4,878
Honor Rancho-Castaic Hills	1950	Fault and stratigraphic	Sands	33°-38°	4690′- 6650′	Miocene	525	4,943	2,595	6,150
Newhall-Potrero	1937	Anticlinal	Sands	33°-37°	6200′-10500′	Miocene	1,175	24,338	28,597	7,790
Oak Canyon	1941	Anticlinal	Sands	22°-33°	2400′- 7200′	Pliocene and Miocene	350	16,894	5,913	1,384
Placerita Canyon	1949	Fault and stratigraphic	Sands	12°-27°	1300′- 2000′	Pliocene	600	30,632	18,379	9,448
Rincon-Padre	1927	Faulted anticline	Sands	25°-31°	3500′- 6500′	Pliocene	1,350	34,122	46,065	8,327
San Miguelito	1931	Faulted anticline	Sands	29°-34°	5500′- 8000′	Pliocene	375	85,125	31,922	11,613
South Mountain	1916	Anticlinal	Sands	19°-30°	800′- 4500′	Oligocene and Eocene	1,675	23,879	39,998	7,810
Ventura Avenue	1916	Anticlinal	Sands	24°-32°	2400′-12000′	Pliocene	3,075	145,769	448,239	74,429
Miscellaneous others									72,231	9,424
Totals									844,724	157,765
Santa Maria Basin										
Casmalia	1904	Anticlinal	Fractured shale	8.5°-11°	700′- 2800′	Miocene and Oligocene	1,650	10,141	16,732	756
Cat Canyon, E. & W.	1906	Anticlinal	Sands and fractured shale	12°-26°	2400′- 6000′	Pliocene and Miocene	3,475	18,334	63,709	18,305
Gato Ridge	1931	Stratigraphic	Fractured shale	12°-14°	1800′- 3200′	Miocene	500	39,340	19,670	2,939
Lompoc	1903	Anticlinal	Fractured shale	19°-21°	2200′- 2900′	Miocene	2,800	8,053	22,547	5,237
Orcutt	1903	Anticlinal	Fractured shale and sands	18°-26°	1100′- 4280′	Miocene	4,450	25,500	113,476	3,883
Santa Maria Valley	1934	Stratigraphic	Fractured shale and sands	12°-17°	2900′- 5500′	Miocene and pre-Tertiary	7,500	14,684	110,128	11,008
Zaca Creek	1942	Fault	Fractured shale	7°- 8°	5000′- 5100′	Miocene	850	6,315	5,368	4,200
Miscellaneous others									2,251	2,181
Totals									353,881	48,509
Salinas Basin										
San Ardo	1947	Anticlinal	Sands	10°-12°	2100′- 2500′	Miocene	4,700	2,514	11,815	22,626
Miscellaneous others									7	17
Totals									11,822	22,643
San Joaquin Basin										
Belridge—North	1915	Anticlinal	Sands	15°-46°	750′- 9000′	Pleistocene-Pliocene; Miocene-Oligocene	2,475	24,752	61,262	1,623
Belridge—South	1911	Anticlinal and stratigraphic	Sands	13°-30°	750′- 4500′	Pleistocene-Pliocene and Miocene	8,300	6,406	53,173	7,221
Canal	1937	Anticlinal	Sands	39°	8350′	Miocene	1,025	15,885	16,282	1,345
Coalinga Nose and N.E.	1938	Stratigraphic	Sands	30°-33°	7800′- 8200′	Miocene and Eocene	5,000	46,932	234,660	47,648
Coalinga—Old	1896	Stratigraphic	Sands	14°-22°	1200′- 3000′	Miocene and Cretaceous	20,275	22,701	460,270	22,112
Coles Levee—North	1938	Anticlinal and stratigraphic	Sands	32°-54°	9100′- 9900′	Miocene	3,750	18,005	67,519	16,232
Coles Levee—South	1938	Anticlinal and stratigraphic	Sands	35°-37°	9700′	Miocene	3,900	3,205	12,498	2,913
Edison Area	1934	Stratigraphic and fault	Sands and fractured schist	15°-29°	1680′- 4935′	Pliocene-Miocene and basement complex	4,600	9,850	45,312	14,997
Elk Hills	1910	Anticlinal	Sands	21°-38°	3000′- 7750′	Pliocene and Miocene	19,925	10,544	210,088	7,748
Fruitvale	1928	Stratigraphic and fault	Sands	16°-21°	4235′	Pliocene and Miocene	2,900	18,959	54,982	9,212
Greeley	1936	Anticlinal and stratigraphic	Sands	33°-38°	7790′-11500′	Miocene	1,925	28,864	55,564	12,948
Guijarral Hills	1948	Anticlinal and stratigraphic	Sands	31°-40°	8200′- 8900′	Miocene and Oligocene	1,775	9,059	16,079	8,690

Table 1. Pertinent data on principal oil fields of California.—Continued.

Principal fields	Year discovered	Type of accumulation	Type reservoir rock	A. P. I. gravity range	Average or range of completion depths	Age of producing formations	Proved acres to 1/1/53	Recovery bbls./acre to 1/1/53	Total production to 1/1/53 M. bbls.	1952 production in barrels per day
San Joaquin Basin—Continued										
Helm-Lanare	1941	Anticlinal and faults	Sands	30°-60°	6700′- 8100′	Miocene, Eocene, and Cretaceous	4,200	3,115	13,081	2,360
Jacalitos	1941	Anticlinal and stratigraphic	Sands	21°-40°	3800′- 4175′	Miocene	3,350	4,395	14,723	2,462
Kern Front	1912	Stratigraphic and faults	Sands	13°-14°	2200′	Pliocene and Miocene	4,325	18,311	79,195	7,481
Kern River	1899	Stratigraphic and fault	Sands	12°-14°	900′	Pliocene	9,625	33,109	318,671	12,703
Kettleman Hills	1928	Anticlinal	Sands	33°-60°	8300′-10700′	Miocene and Eocene	16,650	23,393	389,494	21,815
Lost Hills	1910	Anticlinal and stratigraphic	Sands	13°-22°	1450′- 1700′	Pleistocene, Pliocene, and Miocene	3,475	20,473	71,144	5,904
McKittrick group	1898	Fault-stratigraphic and anticlinal	Sands	11°-53°	1300′- 5000′	Pleistocene, Pliocene, Miocene, Oligocene, and Eocene	3,850	39,395	151,670	19,530
Midway-Sunset-Buena Vista Hills	1900	Stratigraphic and anticlinal	Sands and fractured shale	12°-28°	1400′- 4800′	Pleistocene, Pliocene, and Miocene	56,950	21,001	1,196,001	60,277
Mt. Poso group	1927	Faults	Sands	13°-17°	1500′- 2500′	Miocene	2,850	40,325	114,925	8,952
Mountain View group	1930	Faults	Sands	15°-30°	5140′- 6250′	Miocene	3,000	18,442	55,325	3,559
Paloma	1939	Anticlinal and stratigraphic	Sands	34°-60°	10400′-11900′	Miocene	6,575	3,732	24,537	7,424
Pleasant Valley	1943	Anticlinal and stratigraphic	Sands	25°-30°	8900′- 9000′	Eocene	675	15,341	10,355	1,965
Poso Creek group	1934	Fault and stratigraphic	Sands	11°-15°	1250′- 2770′	Pliocene and Miocene	2,525	6,851	17,299	3,838
Racetrack Hill	1944	Faulted anticline	Sands	38°-41°	4700′	Miocene	575	8,111	4,661	1,632
Raisin City	1941	Anticlinal	Sands	24°-29°	5100′- 6300′	Miocene and Eocene	1,650	7,503	12,380	4,892
Rio Bravo	1937	Anticlinal	Sands	38°-41°	11460′	Miocene	2,025	31,464	63,714	11,843
Riverdale	1941	Anticlinal	Sands	33°-37°	6700′- 8000′	Miocene and Eocene	1,975	5,703	11,264	2,156
Round Mountain group	1927	Faults	Sands	13°-23°	1635′- 2510′	Miocene	2,500	25,580	63,951	5,506
Strand	1939	Anticlinal and stratigraphic	Sands	34°-35°	8300′- 8530′	Miocene	550	12,945	7,120	624
Tejon group	1935	Fault and anticlinal	Sands	13°-35°	500′- 4700′	Miocene	2,300	4,407	10,135	6,476
Ten Section	1936	Anticlinal	Sands	36°-38°	8500′	Miocene	2,225	23,387	52,036	4,430
Wasco	1938	Anticlinal	Sands and fractured shale	30°-37°	13000′-15300′	Miocene and Eocene	375	13,128	4,923	123
Wheeler Ridge	1922	Anticlinal	Sands	21°-25°	2700′- 9750′	Pliocene-Miocene and Eocene	400	14,525	5,810	1,059
Miscellaneous others									22,905	11,185
Totals									4,003,011	360,885
Cuyama Basin										
Cuyama—South	1949	Faulted anticline	Sands	26°-35°	4000′- 4500′	Miocene	3,050	12,401	37,822	38,096
Russell Ranch	1948	Faulted anticline	Sands	21°-40°	3200′- 3700′	Miocene	1,200	23,841	28,609	15,997
Miscellaneous others									1,112	933
Totals									67,543	55,026
Los Angeles Basin										
Brea-Olinda	1889	Fault and anticlinal	Sands	19°-28°	2500′- 3900′	Pliocene and Miocene	1,875	117,359	220,049	18,930
Coyote—East	1911	Anticlinal	Sands	19°-27°	3300′- 6400′	Pliocene and Miocene	1,575	41,347	65,121	7,485
Coyote—West	1909	Anticlinal	Sands	13°-33°	4200′- 7000′	Pliocene and Miocene	1,175	149,637	175,823	9,113
Dominguez	1923	Faulted anticline	Sands	26°-33°	4800′- 8000′	Pliocene and Miocene	1,200	163,379	196,055	10,620
El Segundo	1935	Anticlinal and stratigraphic	Conglomerate and fractured schist	20°-23°	7350′- 7450′	Miocene and basement complex	600	20,722	12,433	246
Huntington Beach	1920	Anticlinal and faults	Sands	13°-28°	2350′- 5000′	Pliocene and Miocene	4,225	118,982	502,699	59,533

Table 1. Pertinent data on principal oil fields of California.—Continued.

Principal fields	Year discovered	Type of accumulation	Type reservoir rock	A. P. I. gravity range	Average or range of completion depths	Age of producing formations	Proved acres to 1/1/53	Recovery bbls./acre to 1/1/53	Total production to 1/1/53 M. bbls.	1952 production in barrels per day
Los Angeles Basin—Continued										
Inglewood	1924	Faulted anticline	Sands	19°-33°	2300′- 8375′	Pliocene and Miocene	875	211,170	184,774	13,617
Long Beach	1921	Faulted anticline	Sands	19°-29°	4400′-10600′	Pliocene and Miocene	1,550	494,387	766,300	21,756
Montebello	1917	Faulted anticline	Sands	22°-36°	3300′- 9000′	Pliocene and Miocene	1,550	102,866	159,442	5,235
Newport group	1945	Fault	Sands	14°-26°	1400′- 5500′	Miocene	1,025	14,175	14,529	4,081
Playa del Rey	1929	Anticlinal and stratigraphic	Sands, conglomerate, and fractured schist	21°-24°	4650′- 6300′	Pliocene, Miocene, and basement complex	600	93,733	56,240	1,598
Richfield	1919	Anticline	Sands	17°-24°	3800′- 4200′	Pliocene and Miocene	1,500	79,445	119,168	6,591
Rosecrans-Athens	1924	Anticline	Sands	29°-42°	4450′- 8700′	Pliocene and Miocene	900	78,011	70,210	4,601
Santa Fe Springs	1921	Anticline	Sands	29°-33°	3500′- 8500′	Pliocene and Miocene	1,500	362,531	543,796	14,109
Seal Beach-Alamitos	1926	Faulted anticline	Sands	22°-33°	5125′- 8200′	Pliocene and Miocene	675	193,646	130,711	11,156
Torrance	1922	Anticlinal and stratigraphic	Sands	12°-27°	3175′- 5300′	Pliocene and Miocene	6,425	21,135	135,795	6,859
Wilmington	1936	Faulted anticline	Sands, conglomerate, and fractured schist	13°-32°	2500′- 6000′	Pliocene, Miocene, and basement complex	6,900	87,799	605,814	131,477
Miscellaneous others									118,066	10,269
Totals									4,077,025	337,276
STATE TOTAL									9,358,006	982,104

constant increase to, and including, the year of 1952. The accompanying oil production graph (fig. 2) clearly illustrates this trend.

The demand for petroleum products during World War II has been maintained at a slightly increased rate during the post-war period. From the modest 12,000 barrels per day at the turn of the century, California production has grown to an average of 982,000 barrels daily during 1952. To this latter figure must be added some 88,000 barrels daily of natural gasoline and condensate to bring the total liquid hydrocarbons being produced at the beginning of 1953 to slightly more than 1,000,000 barrels daily.

At the present time, California stands second only to the state of Texas in crude-oil productive capacity, and provides approximately one-sixth of the nation's oil output.

The oil fields of California (fig. 1), and particularly those of southern California, are unique in some respects among the fields of the world. In few other places are the natural reservoirs for the accumulation of oil and gas so rich and of such thickness or vertical extent. The aggregate thickness of oil-producing zones in the California fields commonly is measured in thousands of feet and, in effect, is equivalent to several normal fields of other regions, piled one upon another. These extensive producing zones explain the high recoveries per surface acre that have been recorded for many fields. The accompanying tables contain pertinent summary data on the more important oil fields of California.

Oil Production by Geologic Ages. Oil and gas production in California is obtained almost wholly from rocks of Tertiary or younger age. The greater portion is produced from sands, with lesser amounts from fractured shales. Oil is obtained in a few localities from fractured metamorphic rocks of pre-Tertiary age. Accumulation in such rocks, however, is clearly by migration from closely associated oil-bearing sediments.

Many California fields produce exclusively from rocks of Pliocene or Miocene age, or from a combination of these. It is estimated that at least 75 percent of the total oil recovered to date has come from the Pliocene and Miocene parts of the Tertiary section, which illustrates the economic importance of these two geologic ages to the petroleum industry in the State.

Production of Oil by Surface Areas. The total recorded production of oil from the State of California to January 1, 1953, was 9,358,006,000 barrels. This output of nearly 10 billion barrels has been obtained from an aggregate of approximately 305,600 acres of oil-productive land, and represents an average recovery to date of approximately 30,600 barrels per acre. It is interesting to note that the maximum recovery to date is in the Long Beach field, which, as of January 1, 1953, has produced 497,387 barrels per surface acre. Several other fields in the Los Angeles basin also have established unusually high recovery records. At the beginning of 1953, the aggregate oil-productive area of California, representing 232 individual oil fields, amounted to approximately 0.3 percent of the surface area of the State.

Production of Gas. Prior to 1927, practically all of the gas produced in California was oil-well or wet gas produced with the oil. Much of this gas was flared or blown to the air because there was no market for such quantities as were being produced. By 1927, however, natural gas had completely supplanted artificial gas for both domestic and industrial uses in the Los Angeles basin and in principal cities elsewhere in the State.

In 1929, laws were enacted prohibiting the wasting of natural gas in California. This caused a sharp reduction in over-all gas production in the State, and the reduction could be noted for several years. Wastage has been less than 2 percent annually during recent years.

The graph in figure 3 illustrates the gas production in California since 1906. No reliable figures are available for production prior to that date.

In the late thirties, an aggressive campaign was started to develop dry-gas supplies. Since then, approximately 35 fields that produce dry gas exclusively have been discovered, mostly in the Sacramento Valley and northern San Joaquin Valley (fig. 1). At the present time, the gas fields aggregate a productive area of about 58,500 acres. Nearly half of this acreage is in the Rio Vista gas field in Solano and Contra Costa Counties. This one field contributes approximately 25 percent of the State's annual current production (for the year 1952) of 475,863,000 Mcf. of gas.* Most of the State's dry gas is produced from Eocene rocks, and lesser amounts are obtained from Cretaceous and Pliocene rocks. Very little dry gas is produced from the Miocene section in California.

Recycling operations were begun on a small scale in California about 1935. In this process gas is re-injected into producing formations after the natural gasoline and liquefied petroleum gases have been removed from it. During the past 10 years, unitized operations in several of the major fields have brought about a large increase

Table 2. California oil and gas production 1900 through 1952.

Year	Oil prod.* M bbls.	Daily avg. oil prod.	Number prod.** oil wells	Gas prod.*** M.c.f.	(M.c.f.) daily avg. gas prod.
1900	4,324	11,847		Not available	Not available
1901	8,786	24,071		Not available	Not available
1902	13,984	38,312		Not available	Not available
1903	24,382	66,800	2,608	Not available	Not available
1904	29,649	81,008	2,713	Not available	Not available
1905	33,427	91,581	2,456	Not available	Not available
1906	33,099	90,682	2,426	20,465,000	56,068
1907	39,748	108,899	2,827	28,570,000	78,274
1908	44,855	122,555	3,399	33,920,000	92,678
1909	55,472	151,978	3,919	40,565,000	111,137
1910	73,011	200,030	4,692	64,960,200	177,973
1911	81,134	222,285	5,138	73,492,389	201,349
1912	87,273	238,451	5,626	76,376,581	208,679
1913	97,789	267,915	5,870	86,812,485	237,842
1914	99,775	273,356	6,106	96,446,996	264,238
1915	86,592	237,238	6,532	78,962,847	216,337
1916	90,952	248,503	7,333	80,105,684	218,868
1917	93,878	257,200	8,053	93,329,401	255,697
1918	97,532	267,211	8,606	102,678,908	281,312
1919	101,183	277,214	9,127	114,597,010	313,964
1920	103,377	282,451	9,621	116,543,705	318,425
1921	112,600	308,493	9,978	128,069,172	350,874
1922	138,468	379,364	8,916	157,791,724	432,306
1923	262,876	720,208	9,396	327,879,088	898,299
1924	228,933	625,500	11,319	267,738,943	731,527
1925	232,492	636,964	11,069	215,165,348	589,494
1926	224,673	615,542	11,333	216,899,860	594,246
1927	231,196	633,414	11,284	249,822,625	684,446
1928	231,811	633,363	10,711	295,665,017	807,828
1929	292,534	801,463	10,515	536,451,029	1,469,729
1930	227,329	622,819	9,454	525,560,068	1,439,891
1931	188,830	517,342	8,612	365,994,081	1,002,724
1932	178,128	486,689	9,039	262,998,491	718,575
1933	172,010	471,260	10,987	256,555,452	702,892
1934	174,305	477,548	11,750	270,535,929	741,194
1935	207,832	569,403	12,971	300,278,754	822,682
1936	214,773	586,811	12,369	322,692,624	881,674
1937	238,521	653,482	13,673	332,567,875	911,145
1938	249,749	684,244	13,979	351,947,787	964,241
1939	224,354	614,668	14,844	353,687,873	969,008
1940	223,881	611,697	15,359	360,974,982	986,270
1941	230,263	630,858	16,979	371,070,381	1,016,631
1942	248,326	680,345	18,909	398,749,778	1,092,465
1943	284,188	778,597	20,012	448,987,569	1,230,103
1944	311,793	851,893	21,476	522,740,472	1,428,253
1945	326,482	894,471	22,215	523,714,244	1,434,834
1946	314,713	862,227	23,177	502,844,572	1,377,656
1947	333,132	912,690	24,412	551,144,705	1,509,985
1948	340,074	929,164	26,456	571,643,112	1,561,866
1949	332,839	911,888	24,341	546,026,479	1,495,963
1950	327,607	897,553	28,073	533,808,851	1,462,490
1951	354,467	971,142	29,624	513,272,810	1,406,227
1952	359,450	982,104	30,889	475,863,000	1,300,172

* Source: California Div. Mines, Bulletin 118, for years 1900-39 incl.; American Petroleum Inst., Facts and Figures, for years 1940-52 incl.
** As of December of each year. Source: Conservation Committee of California Oil Producers.
*** Source: California Div. Mines, Bulletin 118, for years 1906-39 incl.; Am. Gas Assoc., reports for years 1940-52 incl.

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* Data from Southern California Gas Company.

in the amount of gas re-injected to maintain reservoir pressures. During 1952, nearly 1 cubic foot of gas was re-injected for every 2 cubic feet that were made available for consumption.

Reserves of Oil and Gas. Proved crude-oil reserves in California at the beginning of 1953 were estimated to be 3,854,171,000 barrels.* In addition, an estimated 322,507,000 barrels * of natural-gas liquids brought the total recoverable reserves of liquid hydrocarbons to 4,176,678,000 barrels * as of January 1, 1953. Discoveries of new supplies in recent years have not kept abreast of withdrawals, but developments within the known fields constantly require upward revisions of estimates of the remaining reserves, which has had the effect of largely offsetting the withdrawals. How long the reserves of California can be maintained at the present or at higher levels is problematical in the face of ever increasing demands resulting from the industrial and population growth of the State during the last decade.

California's motor-vehicle registration of approximately 5½ millions ** as of January 1, 1953, is the largest of any state in the nation, and has its greatest concentration in Los Angeles County, where about 2¼ million vehicles ** were registered at the beginning of 1953. This concentration has created an exceptionally large motor-fuel demand in southern California.

Producers in the Pacific Coast region have found it necessary to import foreign crude oil to supply the demand for refined products during the last 2 years. In 1952, these imports averaged 32,000 barrels daily, and all indications point toward an increase in the future.

Gas reserves of California, including both dry-gas and oil-field sources, were estimated to be 9,340,022,000 Mcf *† as of January 1, 1953. Local gas supplies have not been sufficient to meet the demands in recent years, and in the first quarter of 1953 approximately 900,000 Mcf. per day was being brought into California through pipe lines from west Texas and New Mexico.

Acknowledgments and References. The writer wishes to make acknowledgment and express appreciation to Mr. M. T. Whitaker for helpful suggestions and criticism, and to the Conservation Committee of California Oil Producers for supplying some of the statistical information quoted in this paper. Free use has been made of data previously published in Bulletin 118 of the California State Division of Mines, and in various publications of the American Petroleum Institute and the American Gas Association.

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* Data from American Petroleum Institute.

** Data from State Department of Motor Vehicles.

*† Data from American Gas Association.

4. STRATIGRAPHIC TRAPS FOR OIL AND GAS IN THE SAN JOAQUIN VALLEY [*]

By Harold W. Hoots,[†] Ted L. Bear,[†] and William D. Kleinpell [**]

Introduction. The depositional and structural history of the San Joaquin basin during the Cenozoic era was ideal for the repeated development of almost every variety of trap for oil and gas. Although most, and possibly all, of the closed anticlines and the more obvious fault traps have been tested and found productive, conditions in this basin are suitable for the existence of many stratigraphic traps that have not as yet been recognized.

Stratigraphic traps of several different types are responsible for the accumulation of oil and gas in the Midway-Sunset, East Elk Hills, Kern River, Edison, North Coles Levee, South Coles Levee, Coalinga (Miocene), East Coalinga (Eocene), and Guijarral fields. Most, if not all, of these fields depend for their existence and/or their size upon lateral differences in subsurface stratigraphy, porosity, or structure that were not apparent prior to discovery.

It is to be expected that recognition and discovery of additional traps for oil and gas will depend upon, and will keep pace with, the extension of exploratory drilling into new areas, and to depths that are now untested. Some of the different types of producing stratigraphic traps are noted and illustrated in the following paragraphs.

Sand Lenses in Converging Near-Shore Sections. Sand lenses in converging near-shore sections were deposited in marine and brackish waters during the Eocene, Oligocene, Miocene, and Pliocene epochs. They occur also in continental upper Miocene and lower Pliocene sediments of the Bakersfield area. They are effective as traps for oil where they thin in up-dip directions and where their pinch-out lines cross localities of relatively high structure. In most instances the effective trap is restricted to the axial part of a basinward plunging nose, but in other, more expansive traps, such as those of the middle Miocene sands of Coalinga and the Eocene Gatchell sand of East Coalinga, the areas of accumulation extend to, and may even include, parts of adjoining synclines.

The near-shore marine sand lenses of this type appear to have been formed at times when the sea either was occupying a relatively static position, or was expanding and actively transgressing adjoining land areas. The Gatchell-Cantua sand lens of the Coalinga-Cantua Creek area (fig. 1) may be an example of the former, whereas the Etchegoin and Tulare Buttress sands of the Midway-Sunset-McKittrick district (fig. 2), and the middle Miocene Lower Duff sand of the Edison field definitely are examples of the latter.

The oil-producing Etchegoin sands of Buena Vista Front and the eastern part of Elk Hills occur in a southwestward thinning section of beds that were deposited along the northeast flanks of anticlines as these folds were growing from the floor of the Etchegoin sea.

Sand Lenses and Permeability Barriers in Basinward Areas. The Stevens zone of the upper Miocene section constitutes the most distinct and widespread major lens of sand in the Tertiary of the San Joaquin basin (fig. 3). Considered broadly, it grades eastward into near-shore marine Santa Margarita sand and nonmarine beds of the Chanac formation.

The Stevens sand thins and grades laterally into shale and cherty shale to the west, north, and south in a manner establishing its derivation principally from lands that lay to the east and southeast. It was deposited in a sea that extended far beyond the San Joaquin basin, but, by coincidence, it attains its greatest thickness along the axial part of the present geosyncline.

Even where it is productive, sand of the Stevens zone characteristically has relatively low permeability, owing to the presence of a white interstitial pasty substance. This feature is particularly evident in areas of appreciable thinning of the main Stevens sand, with the common result that oil-stained sands in structually favorable pinch-out areas prove to be too tight to produce. This lack of effective permeability is pronounced in the main Stevens sand zone at the eastern end of the Elk Hills anticline, a locality where the sand is still thick, and it provides an effective barrier to oil migration. It accounts for the fact that the area of the North Coles Levee field, within this main zone, is much larger than the area of local anticlinal closure. A similar permeability barrier within the Eocene Gatchell sand of Coalinga Nose accounts for the presence of the Pleasant Valley field (fig. 1).

Some indivdual sands of the Stevens zone, particularly the stratigraphically higher ones, maintain fair to moderate permeability throughout their extent and provide effective traps for oil in areas of favorable structure. Excellent examples are the 21-1 sand of the North Coles Levee field and the F-1 sand of the South Coles Levee field, which pinch out as they cross diagonally the axes of anticlinal folds (fig. 4).

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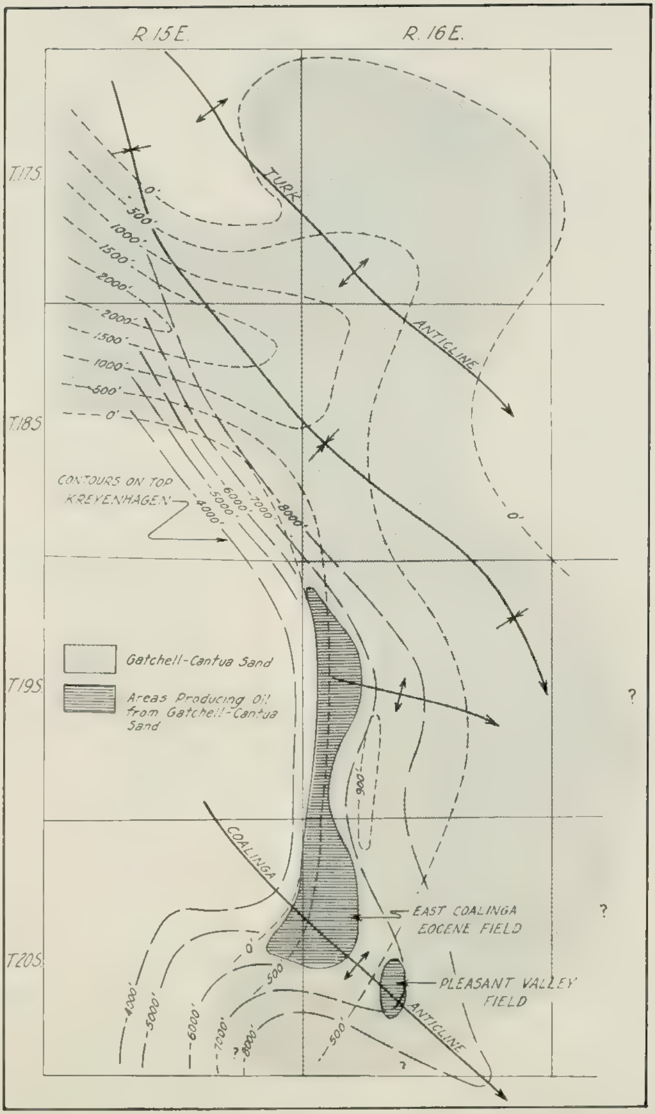

FIGURE 1. Structure-contour map of the Coalinga-Cantua Creek area, showing the distribution and thickness of the Gatchell-Cantua sand.

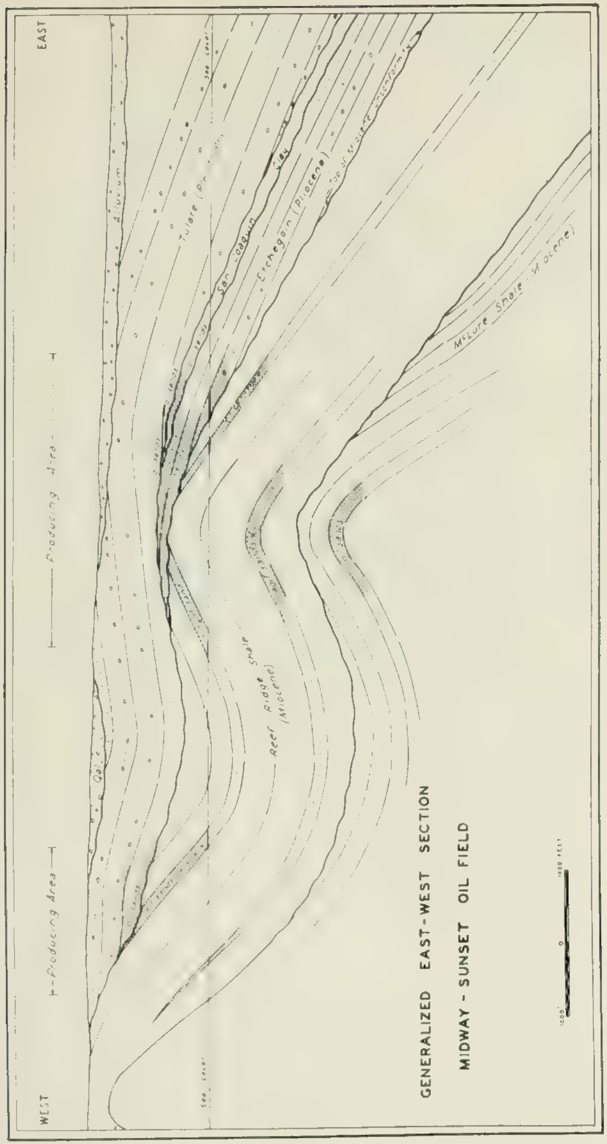

FIGURE 2. Generalized structure section across the north Midway-Sunset oil field, illustrating the Pliocene-Miocene unconformity and its importance in providing traps for oil and gas in Pliocene-Pleistocene sands above and in Miocene sands below.

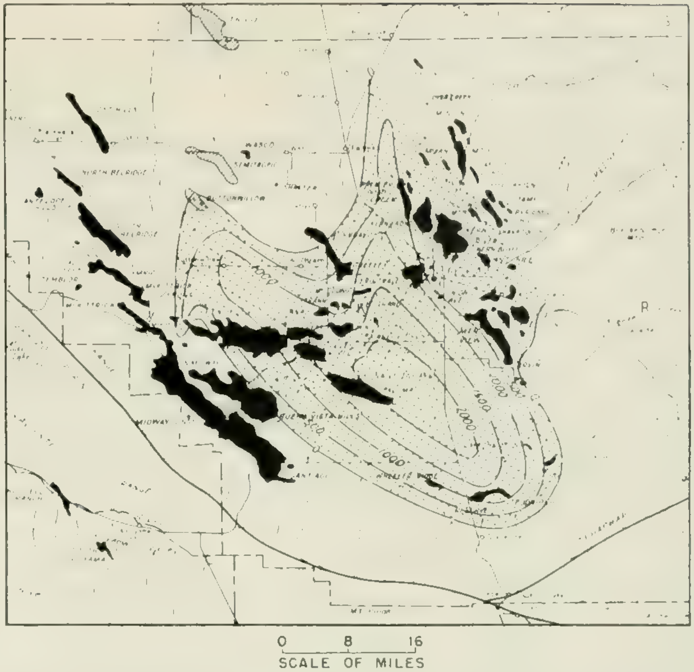

FIGURE 3. Map of oil fields in the south part of the San Joaquin Valley, showing distribution and thickness of the Stevens sand zone (upper Miocene) and its age equivalent to the east and southeast.

Truncated Sands Beneath Unconformities. Unconformities of both local and regional extent abound in the Tertiary section of the San Joaquin basin, and several of them are accompanied by perceptible angular discordance that clearly is responsible for oil accumulation. The most important one separates Pliocene beds from Miocene beds along the west side and southern end of the basin, and is characterized by angular discordances of 20° to 30°; it traps oil in the underlying, more steeply dipping Miocene sands in structurally high areas throughout the Midway-Sunset-McKittrick district (fig. 2).

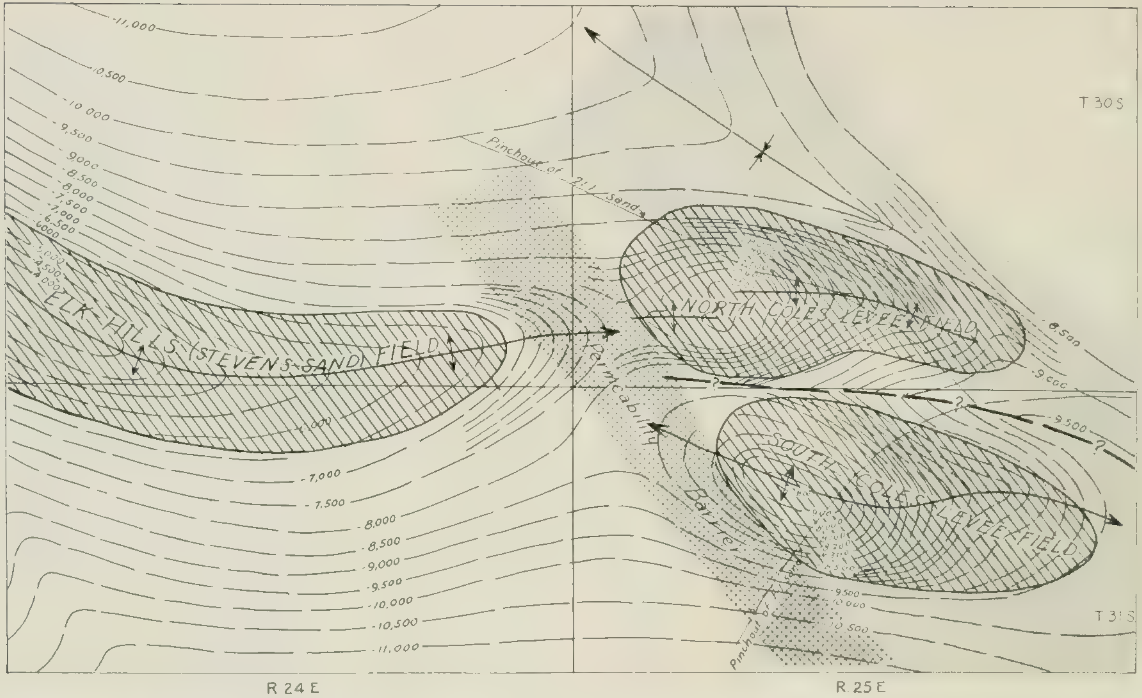

FIGURE 4. Structure-contour map of the Elk Hills-Coles Levee area, showing (1) permeability barrier in main Stevens sand separating the Elk Hills (Stevens sand) field on the west from the North Coles Levee and South Coles Levee fields on the east, (2) pinchout of 21-1 sand lens across North Coles Levee anticline, and (3) pinchout of F-1 sand lens across South Coles Levee anticline.

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

CHAPTER X

ENGINEERING ASPECTS OF GEOLOGY

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Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

CHAPTER X

ENGINEERING ASPECTS OF GEOLOGY

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Editorial Note:

CHAPTER TEN deals with several of the more serious geologic problems that confront the resident of southern California. The highly varied topography and climate of the region, together with the complexity of its rocks and their structure, form a background of physical factors that cannot be ignored in the development of this region by man. Some of these factors are related directly to floods, earthquakes, mass movement of ground, and other recurring events over which man has little fundamental control, and others are developed by some of man's own activities. Failure to anticipate or properly to evaluate these factors during past development of the region has led to unfortunate, and at times disastrous, consequences.

Only during recent years has there been widespread recognition of the need for careful geologic appraisal of engineering problems in southern California. Normal study of the positive factors in location and design of buildings, dams, aqueducts, and other structures, for example, is now being supplemented by consideration of the nature and movement of solid and liquid materials in the subsurface, the position and behavior of active faults in the area, the movement of surface water in the area during previous centuries, and other features that are likely to have significant long-term effects. Typical avenues of geologic approach to several major engineering problems are discussed in the three papers that make up this chapter.

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1. EARTHQUAKES AND EARTHQUAKE DAMAGE IN SOUTHERN CALIFORNIA*

By Charles F. Richter †

Intensity Scales

Although problems of the seismic activity of any region or of the world are best handled in terms of the earthquake magnitude scale, this scale will not serve the needs of the engineer and field geologist who wish either to relate effects on structures, ground, and ground water to the intensity of local shaking, or to interpret intensity in terms of surface and subsurface structure and the generating mechanism of earthquakes. The magnitude scale attaches a single number to the earthquake as a whole (see Richter and Gutenberg, Contribution 3, Chapter IV); for detailed statement of the variation of effects from point to point an intensity scale is needed.

Ideally, intensity should be determined from complete instrumental recording of motion at the point in question. Seismographs commonly in use have high magnifications, run off the recording sheet if the motion is strong enough to be felt, and are put out of action by high intensities. Strong-motion seismographs have been constructed with low magnification, usually triggered to begin recording during a locally strong earthquake, but even these instruments are expensive to construct and maintain. In the last 20 years many records have been obtained from such instruments, chiefly in California, by the U. S. Coast and Geodetic Survey. They represent the motion at only a few localities for each earthquake.

Mr. Frank Neumann, at the Coast and Geodetic Survey office in Washington, is now engaged in a synthetic study of these records—a study aimed at placing the intensity scale on a sound physical basis. It is not yet possible to anticipate final results in this direction. The many thousands of seismograms of earthquake motion too small to be felt show a complexity and a difference between individual shocks which indicate that generalizations should be undertaken only with great caution; further, there is good reason for believing that the vibrations are still more complex in large earthquakes.

Under these circumstances, intensity still must be rated in the established fashion, i.e., from field observations of the effects on structures, loose objects, and the ground itself. Long experience shows that certain earthquake effects tend to appear together as the intensity increases, and the published scales consist of a grouping of such effects under a series of arbitrary grades, which are usually designated by Roman numerals to emphasize that the intensity number does not stand for a physically measured quantity. Many efforts have been made to correlate these intensity numbers with some physical element of the earthquake motion, usually acceleration. Such a relation is that published by Gutenberg and Richter (1941):

$$\log a = I/3 - 1/2$$

Here I is the intensity number on the modified Mercalli scale of 1931, and a is acceleration in cm sec^2. It must be emphasized that this relation is extremely rough and empirical, and by no means should be used for any precise work.

The Rossi-Forel scale, commonly used and best known for many years, is as follows:

1. *Microseismic shock.*—Recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.
2. *Extremely feeble shock.*—Recorded by several seismographs of different kinds; felt by a small number of persons at rest.
3. *Very feeble shock.*—Felt by several persons at rest; strong enough for the direction or duration to be appreciable.
4. *Feeble shock.*—Felt by persons in motion; disturbance of movable objects, doors, windows; cracking of ceilings.
5. *Shock of moderate intensity.*—Felt generally by everyone; disturbance of furniture, beds, etc.; ringing of some bells.
6. *Fairly strong shock.*—General awakening of those asleep; general ringing of bells; oscillation of chandeliers; stopping of clocks; visible agitation of trees and shrubs; some startled persons leaving their dwellings.
7. *Strong shock.*—Overthrow of movable objects; fall of plaster; ringing of church bells; general panic; without damage to buildings.
8. *Very strong shock.*—Fall of chimneys; cracks in the walls of buildings.
9. *Extremely strong shock.*—Partial or total destruction of some buildings.
10. *Shock of extreme intensity.*—Great disaster; ruins; disturbance of the strata, fissures in the ground, rock falls from mountains.

When the imperfections in this scale became increasingly evident, an improved scale was constructed by Mercalli. This still retained too close reference to conditions that were specifically European, so that the modified Mercalli scale of 1931 was constructed for application in the United States, especially in California, with the intention of retaining general applicability as far as possible. Its summarized form is as follows:

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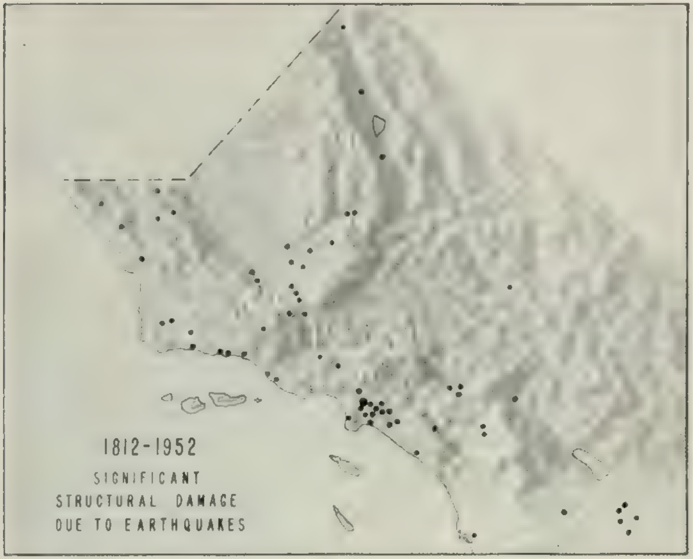

FIGURE 1. Relief map of southern California showing areas where significant structural damage has been caused by earthquakes during the period 1812-1952.

I. Not felt except by a very few persons under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all; many persons frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII. Damage slight in specially designed structures; considerable and with partial collapse in ordinary substantial buildings; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well waters. Disturbs persons driving in motor cars.

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb; great damage in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any, masonry structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Anyone working with actual data should use the complete form of this scale. The Rossi-Forel scale, which included reference to different types of instruments that were not specified, rapidly became obsolete. Similarly, the 1931 scale refers to different types of construction that are not specified closely. Its authors had in mind the construction conditions that were prevailing in 1931, especially in California, as revealed by damage in a large number of earthquakes. Since that time there has been much construction under better conditions of design and inspection; thus, too literal application of the 1931 scale to new structures may lead to an underestimating of intensity. Unfortunately for the community, but fortunately for the intensity scale, many of the older, weaker structures still remain, and by their bad performance provide a check against the response of better designed construction to a shock of given intensity.

The following points are particularly to be noted in applying any intensity scale:

1. Intensity assignments should be based on the entire complex of effects in a given locality; no one criterion should be singled out for use, especially if the evidence is conflicting.

2. Intensity should be that which best represents effects in the locality, aside from individual departures due to peculiarities of structure, ground, or to propagation of elastic waves. It should not

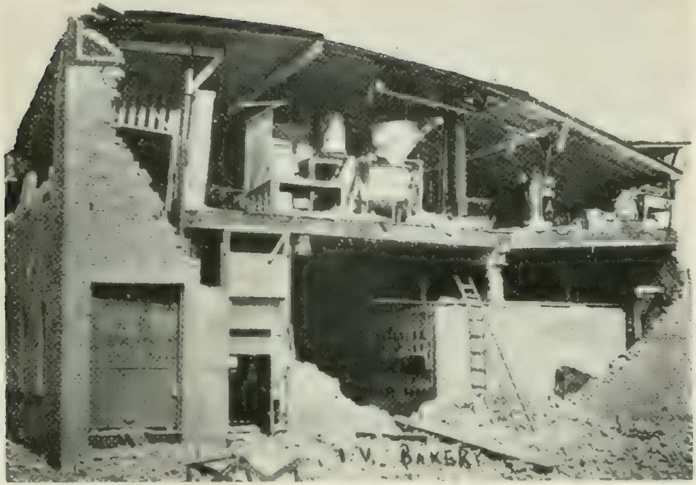

FIGURE 2. Damage to weak masonry, El Centro, 1915. Seis. Soc. Amer., Bull., vol. 5, plate 14.

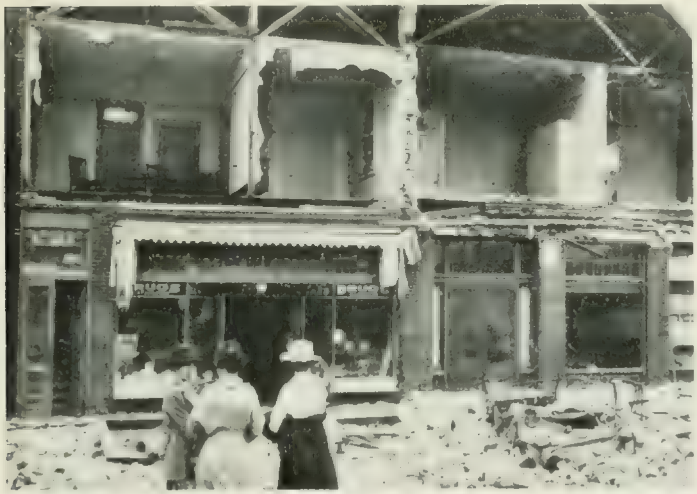

FIGURE 3. Damage to weak masonry, Inglewood, 1920. Separation of bricks was due to weak mortar. Seis. Soc. Amer., Bull., vol. 10, plate 8. *Photo by Los Angeles Times.*

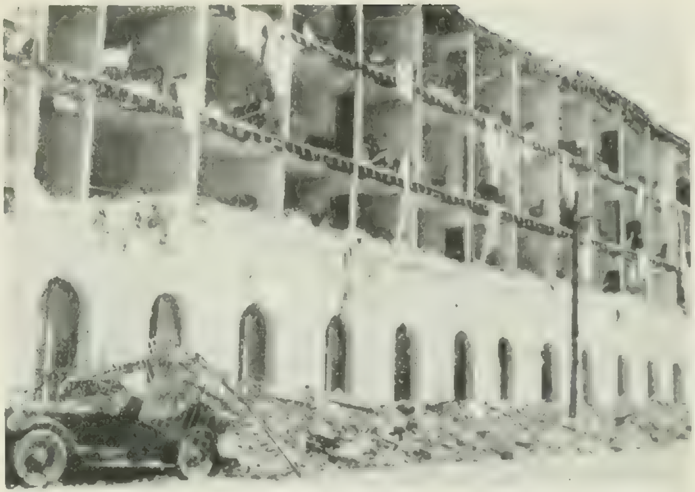

FIGURE 4. Damage to weak masonry, frame structure with brick veneer, Santa Barbara, 1925. Seis. Soc. Amer., Bull., vol. 15, plate 30.

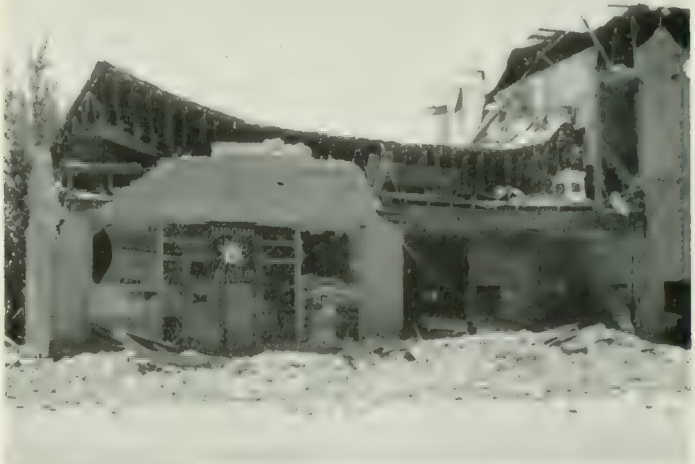

FIGURE 5. Severely damaged building housing Masonic Lodge, Tehachapi, 1952. *Photo by F. E. Lehner.*

be the highest suggested intensity number, nor the lowest; in statistical terms, it should be the mode.

3. How minutely local effects can be considered depends on available information. In the absence of very full data, as in thinly settled areas, care must be taken to consider the effect of ground at the point of observation. Other circumstances being equal, apparent seismic intensity is higher on unconsolidated ground (alluvium, especially where water-soaked; beach sands; artificial fill) than on consolidated ground or on firm rock. This is in part due to slumping, settling, and disturbance of ground water, induced by earthquake vibration. It has also been attributed directly to decrease in velocity of seismic waves entering the less consolidated material. Whatever the cause, this effect normally masks the more naturally expected "cushioning," or absorption of elastic waves passing through soft material. Such cushioning probably occurs to some extent, but in estimating any risk at a given locality, or in drawing any inference from local intensity as to the source of an earthquake, it first should be assumed that intensity is increased in soft ground.

In assigning intensity to an extended area, as in point 2 above, allowance should be made for this effect of ground. Thus small local areas of high intensity that obviously are due to bad ground normally do not appear in isoseismal maps. This may not be best for the structural engineer, but it is convenient for the geologist who is trying to investigate the nature and degree of disturbance in the underlying "basement" rock.

4. Intensity scales combine three principal groups of effects which do not always show close correlation: those due to short-period and to long-period elastic waves, and those due to fault displacement.

Most ordinary effects on structures are due to waves with short periods (0.1 second to 1 second) but relatively high accelerations (100 cm/sec^2 or over). Many effects on large structures, and many of those involving large-scale slumping, sliding, and disturbance of ground water, are connected with waves of period as much as ten seconds, having low accelerations but amplitudes measured in inches or even feet. Such waves are particularly prominent in large earthquakes, especially where there is evidence for considerable linear extent of faulting.

Intensity may not be exceptionally high as measured by elastic-wave vibration in the vicinity, especially when a fault break reaches the surface through unconsolidated material. This was the case in the Imperial Valley earthquake of 1940. At Cocopah (Mexico) an adobe structure straddling the fault trace, where there was a strike-slip displacement of nearly 10 feet, was torn apart and wrecked; in contrast, adjacent structures of the same type, though damaged, were in not much worse condition than others several miles from the fault.

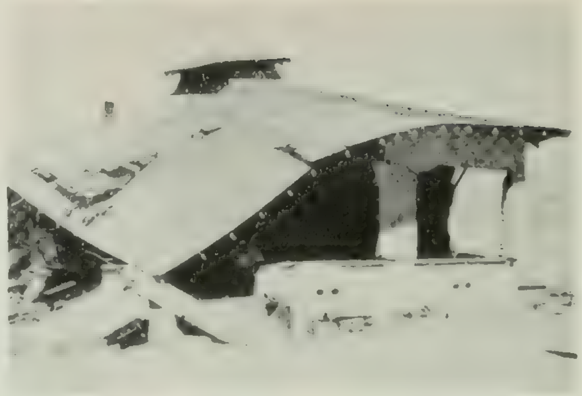

FIGURE 6. Cummings Valley School, west of Tehachapi, 1952. Constructed prior to 1933 of concrete that was nominally but not effectively reinforced. *Photo by State Division of Architecture.*

In applying the intensity scale, it is difficult to eliminate inconsistencies that arise from these causes; they show that the idea of intensity is complex and includes distinct physical quantities that ultimately must be separated.

Damage to Structures

The following notes refer chiefly to damage by elastic waves, usually involving accelerations exceeding one-tenth that of gravity. Very serious damage often is occasioned by slumping or settling, as well. In many instances such mass movements take place in an unstable area that obviously is unsuitable for habitation, and in which the slumping and settling are constantly going on and are merely triggered or accelerated by earthquakes.

Most ordinary structures will not withstand distortion of their foundations. Special construction, however, can be made surprisingly resistant, as shown for example, by the city hall at Lynwood. In anticipation of possible settling in soft ground, this brick building was reinforced at each floor level by diagonal bracing, and a course of cement was laid after every few courses of brick. This structure withstood the Long Beach earthquake of 1933 with almost no damage, whereas most brick structures in the immediate vicinity were seriously damaged and some were almost completely wrecked.

This bears on the vexing question of safe brick construction in an earthquake region. The comments that follow are strictly the writer's own, and he assumes full personal responsibility for them.

As a matter of history, brick construction has had a poor record in connection with California earthquakes. This is due in large measure to fundamentally unsound building practices that obtained during the "boom" period of the 1880's, and which continued in lesser degree down to 1925 and 1933. For many years there was no effective building inspection, especially in smaller communities; such regulations as were enforced were directed against fire and other more frequent risks, and did not consider earthquake risk at all. Some structures were so jerry-built that they developed cracks and failed partially under normal use and loading. Some were repeatedly condemned, nominally repaired in slapdash fashion, and returned to use. Few structures of any type were designed to withstand lateral forces. Extensive falling out of walls at Santa Barbara in the 1925 earthquake drew attention to failure to tie in at the corners, a precaution that has been incorporated in later building codes.

Mortar often has been of poor quality or poorly applied. When a California brick structure is cracked by earthquake motion or by other causes, the cracks almost invariably pass around the bricks, not through them. The Long Beach earthquake of 1933 developed a vast supply of good second-hand bricks; jobbers found that bricks from damaged structures could be cleaned perfectly by hosing off the remains of the mortar, leaving them as good as new.

These evils are not necessary, as the above example of the Lynwood city hall shows. However, in commercial masonry work it is very difficult for the contractors to maintain high standards and still make a profit. Best results, for example, are believed to be obtained by laying up the bricks wet and allowing each course to dry before adding the next. This is a slow and expensive process.

Safer structures have been obtained by making a frame of steel or reinforced concrete, and by using brick principally for filling and facing. Such buildings have behaved comparatively well during recent earthquakes, and actually have been responsible for underestimation of earthquake intensity in their vicinity.

For public buildings, and especially schools, much was accomplished by passage of the Field Act shortly after the Long Beach earthquake. This sets improved standards, including earthquake resistance, for new public construction, and places the responsibility for the safety of old structures on the individual communities, with the State Department of Public Works as inspecting agency. Attempts to weaken the provisions of this legislation have been made almost continuously—so far, fortunately, with no great success.

Ordinarily well-built frame structures are not particularly susceptible to damage, especially in moderate earthquakes. If not well braced diagonally, the frame may be badly wrenched. If the structure is not properly bolted to its foundation, it may slide off and

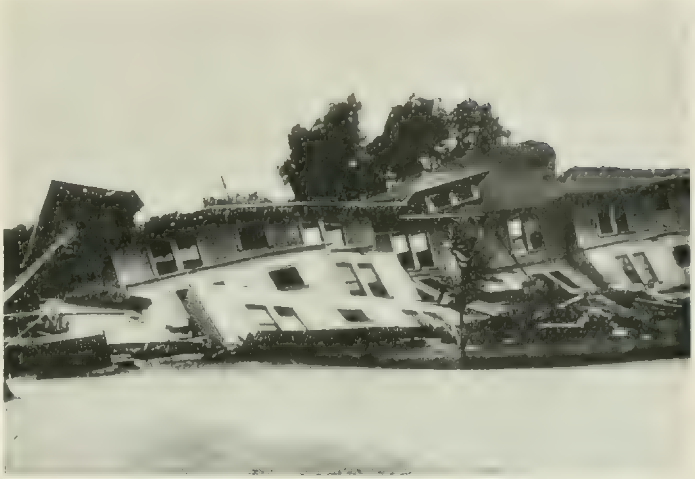

FIGURE 7. Collapse of weak frame structure. Hotel in San Jose, 1906. California Earthquake Commission Report.

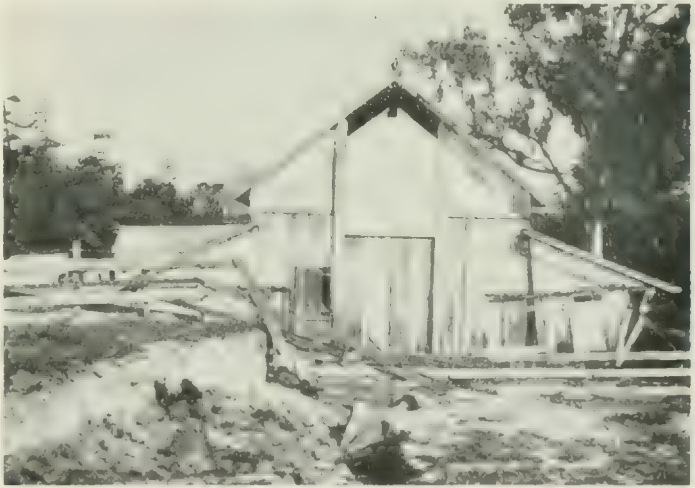

FIGURE 8. Barn not seriously damaged, although fault trace passed under one corner, 1906. Near Olema. California Earthquake Commission Report

hence be seriously damaged. In the 1933 earthquake there was damage to many frame structures supported on vertical posts termed "cripples." As already suggested, steel-frame and reinforced concrete structures, up to moderate size, have performed well except where there were obvious deficiencies in design or workmanship.

The safe design of large structures presents serious difficulties, as the complexity of the dynamical properties of such a structure, combined with the extreme complexity of strong earthquake motion, place the general problem almost beyond the reach of exact analysis. Much progress has been made by investigating the behavior of models on shaking tables, but serious differences of interpretation and opinion still remain among competent specialists. The design problem is now being met by the introduction of safety factors well beyond the limits of any anticipated stress, and by rigid county and city regulations.

Earthquake Risk and Geography

The accompanying map (fig. 1) shows communities and areas in southern California where serious earthquake damage (intensity VIII or over, modified Mercalli 1931) has occurred during the relatively brief period of historic record. Naturally these indications are infrequent in the thinly populated desert and mountain regions. The fact that any one community has escaped in the short time of record is no guarantee of future immunity. It will be noted that the distribution of earthquake damage is rather general.

It is commonly assumed that earthquake risk in southern California is concentrated exclusively near the major faults. This is not the case. At a given point the principal long-term risks involve a great earthquake originating on one of the major faults, up to distances of as much as 50 miles, or a comparatively moderate earthquake, like the Santa Barbara and Long Beach shocks, originating nearby. The distribution of seismicity in California (Contribution 3, Chapter IV) is such that this combination of risk can be considered relatively even over the region. Increased risk is much more a matter of ground. The chief danger spots are the alluviated areas of both coast and interior, and the areas of artificial fill in metropolitan zones. To these must be added the major fault zones, where the crushed and unconsolidated material adds to the probability of damage, even from earthquakes originating elsewhere.

In California, and especially in the more arid sections, disturbance of ground water is a potential source of heavy economic loss. Thus in 1952 there was great loss in Kern County due to failure of wells and springs, which was aggravated by damage to pipe lines and tanks. A less direct effect threatened to be extremely serious; many transformers were thrown down from poles, cutting off power supply to well pumps used for irrigating cotton fields. This was greatly mitigated, however, by prompt emergency action of power-company crews. In 1940 there was very great loss in the Imperial Valley by damage to the irrigation system, partly by disturbance and ejection of ground water (an effect that was still more serious in the Yuma Valley), and partly by fracture and offset of the major canals where they crossed the fault along which movement took place.

The risk of fire after a damaging earthquake is well known, especially since the San Francisco disaster of 1906, when the fire spread unchecked because of water-supply failure. This lack of water was due to destruction of pipe lines near the San Andreas fault. In 1933 the fire-alarm system at Long Beach was put out of action, but the fire companies patrolled their several districts and extinguished many small fires.

Thus, although most direct earthquake damage is due to shaking, the immediate effects of faulting are confined to a narrow zone. There is serious risk of heavy loss by interruption of long-distance utility supplies of all kinds wherever they cross the fault. Effects of interruption of railroad and highway communication also should be considered.

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2. RESIDENTIAL BUILDING-SITE PROBLEMS IN LOS ANGELES, CALIFORNIA

By John T. McGill [*]

Introduction. The floods of January and March 1952 literally brought home to thousands of Los Angeles residents the dangers that can exist in building sites acquired and developed without benefit of geologic knowledge. The cost of this lack of understanding of the ways of nature was measured in loss of life, in millions of dollars of property damage, and in seriously disrupted public services and communications. Many "spur-of-the-moment" remedial measures only managed to compound the difficulties.

This was not the first time that local home owners had suffered such losses, nor is it likely to have been the last. Problems inherent in the natural setting (fig. 1) have become infinitely more acute with rapid population growth in the coastal region of southern California. Rugged youthful mountains and hills have been surrounded by, and ultimately incorporated into, expanding urban communities. Many of these uplands of deformed and broken rocks are more or less anticlinal (e.g., eastern Santa Monica Mountains), and numerous dip slopes of thin-bedded sediments appear on their flanks. The semi-arid climate is another major factor. Virtual restriction of rainfall to the winter months favors early saturation of the ground and rapid run-off from the mountains during heavy storms. Swirling flood waters, after filling the bottoms of usually dry canyons, debouch from their mouths and easily overflow the poorly defined channels on the alluvial plains to spread further havoc on the lowlands.

Adding to such natural hazards, man has been directly responsible for many of his own troubles, mainly in creating problems where none existed before as an unforseen consequence of his modifying and reshaping the landforms to suit his own needs. The replacement of natural vegetation and soil by an impervious cover of closely spaced buildings and broad expanses of paving has greatly increased storm run-off and multiplied its destructive energy. In the preparation of sites for buildings and other works, slopes have been cut with little regard for stable angles, and the excavated materials, thoroughly broken and incoherent, have too often been left readily vulnerable to erosion.

The Major Problems. Building-site problems of a geologic nature are principally matters of drainage and stability. They are likely to occur in combination, because stability problems are frequently a direct and almost immediate consequence of improper drainage. Subsurface water contributes to instability as a result of weight, lubrication of potential slippage surfaces, pore-water pressure, seepage forces, and physico-chemical reactions (e.g., changes increasing the volume and plasticity of clays). Foundation stability varies directly with the bearing capacity of the supporting earth materials, and involves problems of deformation as well as of shear failure.

The major problems are to a large degree intrinsic to the landform on which the building site is located. These relationships are indicated in a general way in table 1.

The frequent occurrence of earth tremors in southern California is a contributing factor to many problems of foundation stability (see also Richter, Contribution 1, this chapter). Special consideration must be given to the rigidity of the materials on which a structure is to be built, as was made abundantly clear during the disastrous Long Beach earthquake of 1933. At that time some of the most severe damage occurred on the poorly drained lowlands in the southern part of the Los Angeles coastal plain. Slope failures also are common during strong quakes, though generally the materials must already be near instability for the vibrations to cause movement of large masses.

Other problems not included in the table are of extreme importance in some places. Wave erosion has resulted in extensive damage to residential properties along the southern shores of Santa Monica Bay. In areas where water supplies must be obtained from the local terrain the occurrence and quality of ground-water become critical matters in the choice of a building site. Intrusion of salt water from the ocean has contaminated and forced the abandonment of many wells in the coastal zone. A shallow water table interferes with sewage disposal where cesspools are used.

Not only are there close relationships among the various problems at a given site, but problems created at one site may bring troubles to other properties as well. Nowhere has this spreading effect of changes made in the natural landscape been more noticeable than in the large post-war subdivisions of the eastern Santa Monica Mountains. During floods, materials lost from the cuttings and fills of higher building sites and access roads move down the slopes onto lower sites and into the canyon bottoms, which quickly become impassable.

Recognition of the Problems. The first requirement in dealing with building-site problems is that they be recognized and properly evaluated. This is by no means a simple matter, as many existing problems are obscure and many potential ones are difficult to anticipate. The possible effects of changes with the passage of time are especially important.

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Table 1. Relationship of major building site problems to landforms in Los Angeles and vicinity.

LANDFORMS OF LOS ANGELES AND VICINITY (see fig. 1)			MAJOR BUILDING SITE PROBLEMS	DRAINAGE PROBLEMS					STABILITY PROBLEMS						
				Surface drainage			Sub-surf.		Slope stability				Foundation stability		
										Man-made slopes			Materials in place		
										Cuts					
				Erosion	Deposition	Standing water	*Seepage into foundations	*Decreasing stability	*Natural slopes	Bedrock	*Overburden	*Fills	Bedrock	*Overburden	*Fills
MOUNTAINS AND PROMINENT HILLS			Ridge tops and summits	/	–	–	–	/	/	/	–	x	/	–	x
			Slopes	x	–	–	x	x	/	x	x	x	/	x	x
			Canyon bottoms	x	x	/	x	/	/	/	x	/	/	x	x
			Coastal terraces	/	–	–	/	/	/	/	/	/	/	/	x
VALLEY PLAINS				/	/	/	/	/	–	–	x	–	–	/	x
LOS ANGELES COASTAL PLAIN	Relatively undissected plains			–	/	/	/	/	–	–	x	–	–	/	x
	Low hills of Beverly Hills-Signal Hill belt			/	–	–	/	/	/	/	x	/	/	/	x
	Landforms of the Coastal Margin	Youthfully dissected Santa Monica Plain	Uplands	/	/	–	–	/	–	–	/	–	–	/	x
			Slopes	x	–	–	/	x	x	/	x	x	/	x	x
			Canyon floors	/	/	/	/	/	–	–	x	–	–	x	x
		El Segundo sand hills		–	–	/	–	/	/	–	x	/	–	/	x

x Widespread.
/ Local.
– Negligible or not applicable.
* Problems involving soil mechanics.

Some engineering background is essential to the geologist who makes an examination of site conditions. He needs a working knowledge of the procedures followed in site preparation and development, including grading, drainage and erosion control, and at least the early phases of construction. He should be familiar with the principles of soil mechanics and foundation design, and with pertinent sections of local building codes and other restrictive regulations. The geologist should if possible consult with architect or builder, as well as with the buyer, in the selection of the land, remembering that the seriousness of a problem depends in part upon the specific use for which the site is intended. He must, above all, keep his own limitations in mind, and he should be prompt in referring matters beyond his capability or jurisdiction to the proper specialists. In particular, the geologist is no substitute for the engineer; instead, he can and should cooperate fully with the engineer for their mutual benefit. For example, he can correlate geologic interpretations with the findings of soil mechanics, thereby obtaining the best quantitative data from which to compute stable slope angles for cuttings in overburden.

The recognition of existing and potential problems is facilitated by the use of a comprehensive check list for the geologic appraisal of the site and its surroundings. Such a guide further insures that the data will be available in a form useful to the engineer. In most cases it is obviously unnecessary or impossible to obtain all of the information listed. Some items will be inapplicable, and estimates may be adequate for others.

Suggested check list for the geological survey of a residential building site in Los Angeles.

- I. TOPOGRAPHY
  - A. Relief
  - B. Terrain elements—ridge tops, slopes, canyon bottoms, terraces, etc.
  - C. Slope measurements for different types of earth materials
    - 1. Slope angles
      - a. Steepest natural slopes
      - b. Angle of repose of cohesionless materials
    - 2. Heights of slopes
  - D. Historic changes in topography
    - 1. Comparison of old contour maps and air photos with recent ones
    - 2. Dates and causes of changes
- II. DRAINAGE
  - A. Surface drainage
    - 1. Drainage basins
      - a. Boundaries and areas
      - b. Run-off
        - 1) Factors influencing run-off
        - 2) Excellence of drainage
        - 3) Records of past floods and standing water
        - 4) Estimates of amounts of water that must be cared for
    - 2. Drainage lines (stream channels) and drainage patterns
      - a. Permanence of streams
      - b. Drainage onto, within, and off of site
      - c. Interference with, or concealment of, natural drainage lines (consult topographic maps and air photos)
  - B. Subsurface drainage
    - 1. Thickness of zone of seasonal wetting and drying
    - 2. Occurrence of ground-water
      - a. Water-bearing materials (aquifers)
      - b. Influence of geologic structures

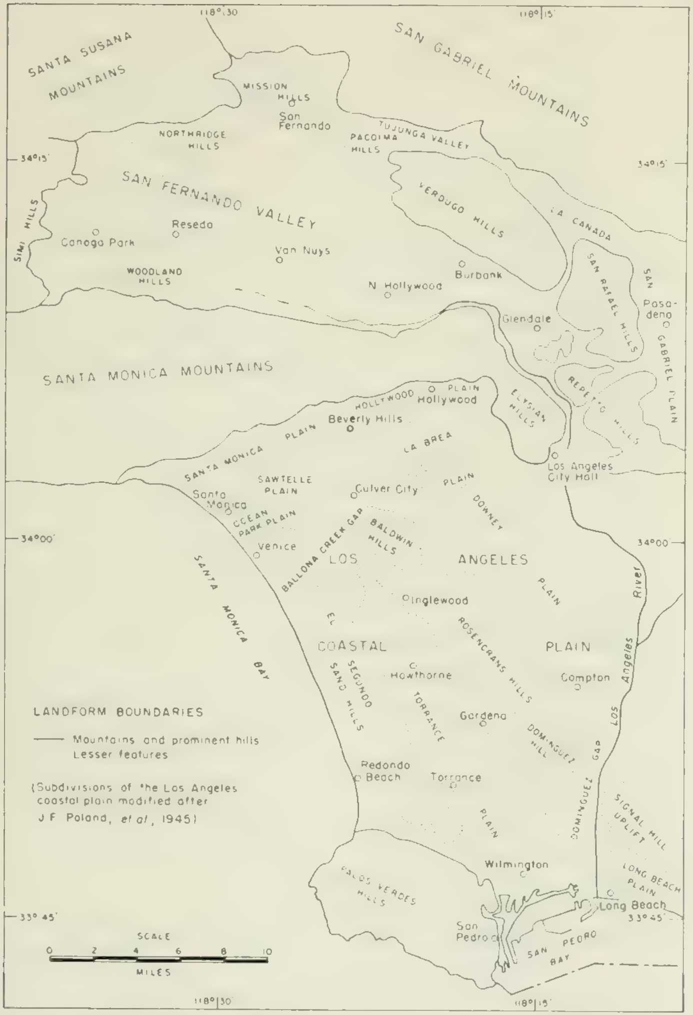

FIGURE 1. Landform map of Los Angeles and vicinity.

- c. Relation to proposed grading and elevations of footings
  - 1) Probable pore-water pressures
- d. Depth and configuration of water table
  - 1) Records of water wells in the vicinity
  - 2) Fluctuations to be expected
- e. Seepages and springs
  - 1) "Quicksand"

3. Movement of ground-water
- a. Paths and rate of movement

4. Quality of ground-water (if it is to be used as water source)

III. NATURAL VEGETATION

A. Types or associations
B. Distribution
C. Historic changes in natural vegetation

IV. EARTH MATERIALS

A. Distribution of earth materials
- 1. Previously published reports and large-scale maps
- 2. Surficial geology
- 3. Extent and relations of earth materials in depth

B. Lithologic characteristics
- 1. As applicable to either bedrock or overburden
  - a. Type, classification, origin
  - b. Homogeneity
  - c. Composition
    - 1) Presence of clay in any form
  - d. Texture
    - 1) Grading of sediments and sedimentary rocks
  - e. Specific gravity of solids
  - f. Unit weight for dry and saturated conditions
  - g. Porosity
  - h. Permeability
  - i. Natural water (field moisture) content
    - 1) Degree of saturation—especially cohesionless materials
  - j. Effects of changing moisture content
  - k. Difficulty of excavation
  - l. Suitability as foundation material
- 2. Bedrock
  - a. Degree of lithification of sedimentary rocks
  - b. Hardness
  - c. Durability
    - 1) Suitability as construction material
- 3. Overburden ("soil" in engineering usage)
  - a. *In situ* materials
    - 1) Residual or transported
    - 2) Degree of natural consolidation
    - 3) Suitability for fill
  - b. Fill
  - c. Results of borings
    - 1) Presence of strong or weak layers at depth
    - 2) Thickness of overburden
    - 3) Elevation and configuration of bedrock surface

C. Geologic structures particularly steeply dipping planes of weakness
- 1. Stratification
  - a. Excellence and continuity of bedding
  - b. Thickness of bedding
  - c. Cross-bedding
  - d. Interbedding of weak layers or pervious water-bearing layers

    2. Foliation
    3. Fractures and fracture zones
       a. Fissures in overburden
       b. Joints—spacing and persistence
       c. Faults
       d. Relationship to other structures
    4. Folds
    5. Dikes, sills, veins
    6. Solution channels
  D. Relationship of lithology and structure to topography
    1. Natural topographic expression
       a. Cliff makers, dip slopes, strike ridges, fault-line valleys, etc.
    2. Existing or proposed excavations
  E. Relative ages of earth materials and of topographic features
    1. Geologic history

V. EARTH PROCESSES OF IMPORTANCE (as judged from past effects, current activity, or likelihood of future operation)
  A. Weathering
    1. Type of weathering
       a. Mechanical, chemical
       b. Spheroidal weathering
    2. Products
       a. Size and shape of disintegrated fragments
    3. Depth
    4. Localization, as along fractures and bedding planes
    5. Rates
       a. Relative resistance of earth materials—differential weathering
    6. Engineering significance
       a. Effects of weathering on stability, ground-water movement, suitability of construction materials, etc.
  B. Mass movement
    1. Location—natural ground, cuttings, fills
    2. Immediate cause
    3. Contributing factors
    4. Type of mass movement
       a. Slope failures
          1) Surface failures—cohesionless materials
          2) Flows—creep, earthflows, mudflows
          3) Slides
             a) Rotational shear slides—typical of clays
                (1) Tension cracks and scarps
                (2) Form and position of slippage surface
                    (a) Base, toe, or slope rupture
                (3) Stress distribution
             b) Detritus slides and falls
             c) Rock slides and falls
                (1) Slippage and break-away surfaces
                (2) Talus
       b. Subsidence—particularly settling of fill
          1) Soft spots, depressions, tension cracks
  C. Erosion and deposition by running water (the site should be examined during or immediately after a heavy rain, if possible)
    1. Ground-water seepage
    2. Rain wash—particularly on canyon side slopes and steep banks
    3. Sheet flood—particularly on surfaces of alluvial fans
    4. Stream flow
  D. Other processes as locally applicable (e.g., work of waves, wind, diastrophism)

VI. WORKS OF MAN
  A. Existing construction—on the site, and on adjoining properties
    1. Date of work
    2. Record of difficulties encountered during and since construction
    3. Condition of foundations and superstructures of buildings (Caution: the condition of buildings on other sites can be misleading)
       a. Settlement cracks
       b. Framing, doors, and windows out of plumb
  B. Future construction—planned or possible
    1. On the site
       a. Probable location with respect to natural features
       b. Proposed contours after grading
       c. Possible effects that might extend beyond the site
    2. On adjoining and upslope properties
       a. Possible effects that might extend to the site

Treatment of Building-site Problems. Unfortunately, it takes more than a beautiful view, nice neighbors, or the convenience of a nearby community center to make a good homesite. Too many wishful home builders have learned to their grief that buying a poor site in the hope of correcting its inherent difficulties is much like marrying a misfit to reform him. The expenses entailed can exceed the combined cost of house and lot, and even then the problems may remain uncontrolled. Sites of the following types are best avoided or abandoned: unstable or very steep natural slopes, the lower parts of closed topographic depressions where run-off collects, and areas located in, or along the unprotected margins of, major drainage channels.

If fair and equable arrangements could be made, many hazardous areas might properly be withdrawn from residential zoning for the good of all concerned. Where this is not feasible, other municipalities could follow the example of the City of Los Angeles in denying grading as well as building permits for places where dangerous conditions would be created. Above all, the property owner must be educated to the possible results of careless reshaping of the landscape. Other things being equal, the best site is the one in which natural topography has been altered the least by cutting and filling. It is also likely to be the most economical site, because extensive grading operations are expensive.

The average building-site problems commonly will respond to the proper preventive or remedial measures, although, to be of any use, the measures recommended by the geologist must be practical as well as realistic. The following remarks provide little more than a brief outline of the techniques of control for some of the problems most commonly encountered. Further details can be found in the references listed at the end of this paper.

1. Erosion of mountain and hill sites by surface drainage. The necessary first step in combating erosion is the improvement of drainage through reduction and control of run-off. Drainage instal-

lations should be sufficient in number, properly placed, and large enough to take care of run-off from intense storms. In order that these installations may be kept in good condition, facilities for inspection and maintenance are essential.

Water can be diverted from man-made slopes by interceptor drains laid in shallow swales behind a berm at the top of the slope. Outlet pipes should extend beyond the toe of the slope. Contour terraces and furrows remove run-off that originates on the slope.

Surface waters should be discharged by ditches or pipes to the nearest practical street, storm drain, or natural water course approved as a safe place to receive them. If prevailing slopes are steep, erosion of ditches can be minimized by constructing the ditches flatter than adjacent grades, and then dropping the ditch over a series of small check dams. Check dams also should be used to control the erosion of gullies. Drain pipes must have adequate slopes to prevent solids from settling and clogging them. Pipes should not empty onto easily eroded natural slopes, and all outfall points must be protected from undercutting by the concentrated run-off. In certain areas where the subsoil is suitably pervious, surface drainage can be discharged to the water table.

In addition to the improvement of drainage, surficial materials can be treated so as to increase their resistance to erosion. Thus asphaltic mixes, concrete, gunite, and riprap are used to line drainage ditches. By far the most effective protective cover for fills is a continuous mantle of vegetation, which not only binds the soil, but helps reduce run-off. The choice of plant species depends upon their adaptability to site conditions and upon the characteristics of the plants. Plants native to the area are generally best, and require a minimum of attention. It is often desirable that plants adapted to more arid conditions be included to insure against complete loss of cover during prolonged periods of dry weather.

Three types of vegetation can be considered in establishing a really permanent cover for uninterrupted protection. Of a temporary nature are the quick-growing grasses, in particular the winter varieties of cereal grains, whose fibrous roots provide rapid binding of the surface layer of soil. The following grasses have been used successfully in this region: Napier grass (*Pennisetum purpureum*), Kikuyu grass (*Pennisetum clandestinum*), Giant reed (*Arundo donax*), Italian ryegrass (*Lolium multiflorum*), Bermuda grass (*Cynodon dactylon*), Giant wild rye (*Elymus condensatus*), and beardless wild rye (*Elymus triticoides*).

The semi-permanent plants are slower-growing but deeper-rooted species that anchor the surface layer to more compact underlying soil. Ornamental vines and sub-shrubs that have had wide popularity in southern California include ivy (*Hedera*), Japanese honeysuckle (*Lonicera japonica*), strawberry (*Fragaria chiloensis*), periwinkle (*Vinca major*), *Lantana*, geranium (*Pelargonium hortorum*), Confederate jasmine (*Trachelospermum jasminoides*), and Mermaid rose (*Rosa bracteata*). Among the larger semi-permanent plants are saltbush (*Atriplex*), Spanish broom (*Spartium junceum*), elderberry (*Sambucus*), and *Baccharis*.

The permanent plants are the shrubs and trees that may take several seasons to establish, but which eventually give a cover comparable to the natural vegetation of nearby slopes. They include *Acacia*, cottonwood (*Populus*), Chinese elm (*Ulmus parvifolia*), pine (*Pinus*), *Eucalyptus*, and Australian tea-tree (*Leptospermum laevigatum*), which is particularly well adapted to very sandy soils.

Planting methods vary with the species and the site. Landscape architects should be consulted regarding the use of vegetation.

2. Standing water. Slopes must be continuous and of sufficient inclination so that water will drain off properly. A gradient of approximately one-half to one foot per 100 feet is necessary for turfed, gravelled, or paved areas.

3. Seepage of subsurface water into foundations. A high water table can be dropped below the level of the foundations by underdraining with pumps or by gravity flow, the choice depending upon the local topography. Pipes are laid in trenches and covered with suitable pervious material backfilled as a reverse filter. Porous concrete pipe with sealed joints, and perforated pipe with the perforations placed down are least likely to clog with fine-grained solids. It is good practice to provide underdrainage where dry stream beds have been filled in during site development.

Upslope diversion of subsurface water by cut-off trenches or walls is sometimes feasible. Treatment of the foundation to render it impermeable may prove expensive where the substructure must be designed to resist water pressures.

A common but rather unsatisfactory solution to the problem is to permit controlled seepage into basement sumps, which are generally emptied periodically by automatic pumps.

4. Subsurface water contributing to instability. Because the presence of excess ground-water is probably the most important cause of slope instability, it is essential that water be kept out of weak or potentially weak earth materials underlying man-made slopes, and in particular away from clay in any form. Water can be prevented from entering critical ground by diversion of run-off and by treatment of the surface to make it impervious. Open cracks in and above cuttings sometimes can be closed satisfactorily by pressure grouting. The filling of tension cracks in clayey overburden retards further drying out which would cause still more cracking. Excess subsurface water already present should be removed by

underdrainage, in order to reduce pore-water pressure and seepage forces, and to prevent the undermining of foundations by erosion of fine-grained material. De-watering increases the strength of the overburden while decreasing its unit weight, and allows for greater compaction of the materials. It will also prevent settlement that might result from later natural lowering of a very high water table. Continuing control of moisture is essential to prevent changes in strength or volume of earth materials.

5. Slope stability. Emphasis in problems dealing with slope stability is understandably placed on preventive rather than remedial measures. It is much easier to counteract potential or incipient failures than to correct these same problems once they get out of hand. Control of most unstable natural slopes, and certainly of all deep deformational slides, is too difficult and expensive for the small property owner.

The foremost requirement for stability of exposed excavation and fill slopes is that they be graded initially to a safe angle. The limiting slope for fills of non-cohesive materials is the angle of repose, which is within the range of 30° to 35° for most natural materials. This is approximately $1\frac{1}{2}$ horizontal to 1 vertical, the gradient recently decreed by ordinance to be the maximum allowable slope for fills within the City of Los Angeles. The presence of an appreciable amount of clay necessitates more gentle slopes, and if the embankment is high, a common practice is to reduce the slope gradually toward the base.

Stable slope angles for cuttings depend mainly upon the physical characteristics and structural attitudes of the earth materials, both of which can vary tremendously even in individual sites. Extremely minor and subtle geologic features often prove to be the dominant factors in stability problems. With the possible exception of homogeneous soft clay or dry non-cohesive materials, stable angles usually cannot be rigidly specified in advance, and thus tabulations of angles are of little practical value and may even be harmful if used for anything more than very general guidance.

The maximum allowable slope for cuttings set forth in the Los Angeles Municipal Code is 1 horizontal to 1 vertical, although deviations from this standard are wisely permitted or required as local conditions warrant. Some strong, sound igneous rocks and hard, massive, flat-lying sedimentary strata have stood virtually unchanged for years in nearly vertical cuttings, whereas cuttings in very soft cohesive soils have failed on the most gentle slopes. Stiff, fissured clays are dangerously misleading, for they may initially stand vertically, yet have a very low permanently safe slope. Obviously, progressive softening and other changes must be taken into consideration in the design of cuttings.

Some indication of the slope stability to be expected for cuttings can be obtained from the steepest natural slopes in the vicinity for the same or similar materials. These are not necessarily the maximum possible values, however, as they reflect only one stage in the physiographic history of the landform on which they occur. The behavior of earth materials also should be closely observed in nearby highway and railroad cuts, and of course during the progress of grading on the site itself.

Excavations should be planned in advance so as to be favorably situated with respect to rock types and geologic structures. In dipping strata it is advantageous to make the cutting along a line at right angles to the strike of the beds. The greatest danger occurs when the bedding planes dip steeply into the excavation, in which case the slope should, if possible, parallel the bedding planes rather than undercutting them.

Long, continuous slopes are broken up into a series of short slopes separated by berms in order to reduce the mass of material and the height of any one slope. Access to the berms permits removal of accumulated debris. Compound slopes should be used if more than one type of material is exposed in vertical sequence within a cutting. Weak material underlying relatively strong material particularly invites rock falls if a uniform slope is used, unless that slope is extremely flat.

Allowance presumably should be made for the effect of frequent earthquakes upon slope stability in southern California. Strong tremors are possibly equivalent in effect to gravity forces acting on a slope some 5° to 10° steeper.

Second in importance to the angle of grading is the mechanical stabilization of the material in the slope. Because so many slope failures in fills can be traced to faulty foundations, it is necessary that the site to receive the fill be prepared in advance. Vegetation and top soil should be removed and the exposed surface scarified. On appreciable slopes, the fill should be compacted upon a series of terraces in addition. Compaction methods employed depend primarily on the cohesive character of the material being used and on the purpose for which the fill is intended. Sheepsfoot, pneumatic, and flat-wheeled rollers, all of which compact by pressure, are best suited to cohesive materials, whereas rammers, which utilize impact, are useful for non-cohesive materials as well. Vibration and inundation are methods favoring non-cohesive materials. Compaction contributes directly to slope stability by increasing the dry density, and thus the shear strength of the materials. By decreasing porosity and permeability, it reduces the likelihood of disrupting seepage forces.

Retaining structures allow more gentle slopes for exposed earth materials, as well as reduction of volume of cuttings and fills. Walls and cribbing support the toes of slopes, and at the same time they prevent undercutting. Stone masonry or plain concrete can be used for low walls. Structures more than 4 feet high should be of reinforced concrete, and should be designed by a competent engineer. Retaining walls are ineffective or actually dangerous unless they are properly drained, because of the addition of a rising hydrostatic head to the earth pressures already present. The usual practice is to backfill a wedge-shaped zone adjacent to the wall with porous sand, gravel, or crushed rock, and to provide weep holes through the wall and some lateral drains behind it. The design of the backfill is fully as important as the design of the retaining wall itself. The best material is coarse and cohesionless, and preferably is compacted so as to give the highest possible angle of internal friction.

Vegetation has only a limited value in stabilizing slopes against mass movement, and that mainly in overburden or fills. Certain plants with deep, stringy roots help to prevent shallow failures. Vegetation should not, however, be expected to hold soil on slopes steeper than the angle of repose under the most unfavorable moisture conditions.

6. Foundation stability. In so far as possible, buildings should be founded directly upon solid bedrock of good structure, or upon overburden possessing a permanently high bearing capacity.

If it is necessary to locate structures on overburden or weak rocks incapable of supporting heavy loads, engineers must resort to treatment of the ground, to special design of the foundation, or to both procedures. Thin weathered zones overlying strong rocks are best remedied by removing them. Weak materials are sometimes replaced with stronger ones, or their properties are modified so as to make them stronger.

Superficial compaction of fills is an even more important factor in foundation stability than in slope stability, because of its effectiveness in increasing the ultimate bearing capacity of the materials. Indeed, the Los Angeles Code specifies that all fills intended to support buildings or structures shall be compacted to at least 90 percent of maximum density. This requirement is usually met by compacting in thin layers with the moisture content carefully controlled at optimum value.

Foundations often can be designed to provide sufficient bearing area to support a small structure with safety even on rather weak earth materials. The load is distributed in area by relatively shallow reinforced concrete mats and spread footings, or it is distributed in depth, as appropriate, by means of friction piles.

The base of a shallow foundation should everywhere extend below the depth of seasonal volume changes of the soil caused by variations in moisture content, and below the zone weakened by root holes and the cavities of burrowing animals. The depth also should take into consideration the possibility of undermining by scour, or of damage from future construction on adjacent lots. To reduce the settlement of shallow foundations, the excavation is sometimes deepened so as to decrease the stress added by the weight of the structure.

Foundations occasionally must be extended downward through the weak materials to sound bedrock or other stronger materials to which the building load can be transmitted. Point-bearing piles, piers, and caissons should be carried below the surface of the strong material, in order to key them in and thereby provide resistance to lateral shearing.

A most difficult problem arises when a building is to be located partly on bedrock and partly on overburden. Either the building is constructed as two independent structural units, or a deep foundation should be carried through the overburden.

In few ways does geology exert a more direct influence on the average citizen than in his selection and development of a homesite. Yet in general this influence is not fully appreciated, sometimes with disastrous consequences. The engineering geologist, through the application of his knowledge of earth materials and processes, is able to provide much needed assistance to home builders in southern California.

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3. SUBSIDENCE OF THE WILMINGTON OIL FIELD, CALIFORNIA

By U. S. Grant *

Introduction. Over a large portion of the Los Angeles coastal plain a slow surface subsidence has been going on for several decades (Nicholson, 1929; Grant and Sheppard, 1939; Grant, 1944; Gilluly and Grant, esp. pp. 463-482, 1949). This widespread subsidence has amounted to a few tenths of a foot. It may have been caused entirely by reduction in artesian water pressure due to excessive well pumping from relatively superficial aquifers, but possibly part of it was caused by depletion of reservoir pressure in early oil fields. In addition to this widespread and relatively slight subsidence, several areas of accentuated subsidence are located in oil fields within the coastal plain. Repeated spirit-level surveys by a number of agencies demonstrate that accentuated subsidence has taken place over the Playa del Rey, Inglewood, Torrance, Santa Fe Springs, Huntington Beach, Long Beach, and Wilmington oil fields. At the present time the maximum subsidence in the Wilmington field has amounted to more than 18 feet (fig. 1).

Initiation of Subsidence in the Wilmington Field. Shortly after significant oil production from the Wilmington field began in 1937, accelerated subsidence of bench marks within the field was noted. Repeated spirit-leveling soon permitted the drawing of isobases (isopleths) of subsidence (fig. 1), which demonstrated that the rapidly sinking area was roughly elliptical in outline, with the major axis of the ellipse approximately congruent with the axis of the elongate domal structure of the oil field. Surface subsidence has progressed continuously with oil production, and the subsiding area covers and extends a little beyond the producing area of the field.

Cause of the Subsidence. An analysis of all possible causes of the subsidence has been recently published (Gilluly and Grant, 1949), and only a consideration of the now generally accepted cause need be included here; namely, compression of sediments due to decrease in hydrostatic pressure in the interstitial fluids of the oil zones. When exploitation of the field began, each oil zone had a reservoir pressure approximately equal to the hydrostatic pressure that would be produced by a column of water extending from the zone to the surface. This fluid pressure supported part of the downward thrust occasioned by the total bulk weight of the overburden of sediments. When oil extraction reduced the fluid pressure, a greater part of the overburden weight was imposed on the granular fabric of the solid part of the oil zone, compressing it vertically. This compression is accomplished in two ways: (1) by rearrangement of discrete grains of the sediment and concomitant squeezing of clayey, limy, or ferruginous cement from points of potential contact between grains to stress shadows in the interstitial voids, and (2) by elastic distortion of the grains themselves. The first phenomenon is essentially irreversible, whereas the second is reversible in part.

Elastic fatigue, flow slips in crystal grains, and reduction in flexural rigidity of the deformed overlying strata through plastic flow and shear rupture, all tend to prevent complete elastic recovery when and if fluid pressures are restored to their original values. The elastic distortion of individual grains is believed to cause but slight change in volume of each grain, although the amount of grain volume change is dependent upon several factors, such as number and effectiveness of constraints to expansion, and Poisson's ratio of the grain material. Therefore artificial repressuring of the oil zones, if done as a corrective measure, can be depended upon to delay or to retard future subsidence, but not to restore completely the original elevations of points on the subsided surface.

Horizontal Displacements Due to Subsidence. A study of the physical facts of the subsidence indicates that the Terminal zone (Upper and Lower Terminal zones combined) has made the greatest contribution to the subsidence, the contributions of the lower zones being additive to that produced by the greater vertical shortening in the Terminal zone above. The depth to the top of the Terminal zone averages about 3,000 feet or a little more, and hence the overlying sediments can be conveniently compared to a plate or prism, 3,000 feet thick, that is deformed by its own body force (gravity) acting on a failing foundation below. An analogue that permits a relatively simple mathematical analysis consists of a plate resting on a vast stratum of coil springs, the subsidence being produced by a central point load or by a uniformly distributed load. It can be seen intuitively that the reaction of the compressed coil springs is unlike that due to vertical pressure exerted on an elastically isotropic continuum. In the latter case, the horizontal expansion of each column of foundation as it is vertically compressed—the Poisson "bulge"—influences contiguous volumes of foundation material, and so on.

This permits an analogy with the deflections of a circular or elliptical plate, clamped at the margins and deformed by a surface load. The analogy requires certain assumptions if the mathematical treatment is to be kept relatively simple. The clamped plate margin is a simplifying subterfuge to produce an inflection in the subsidence

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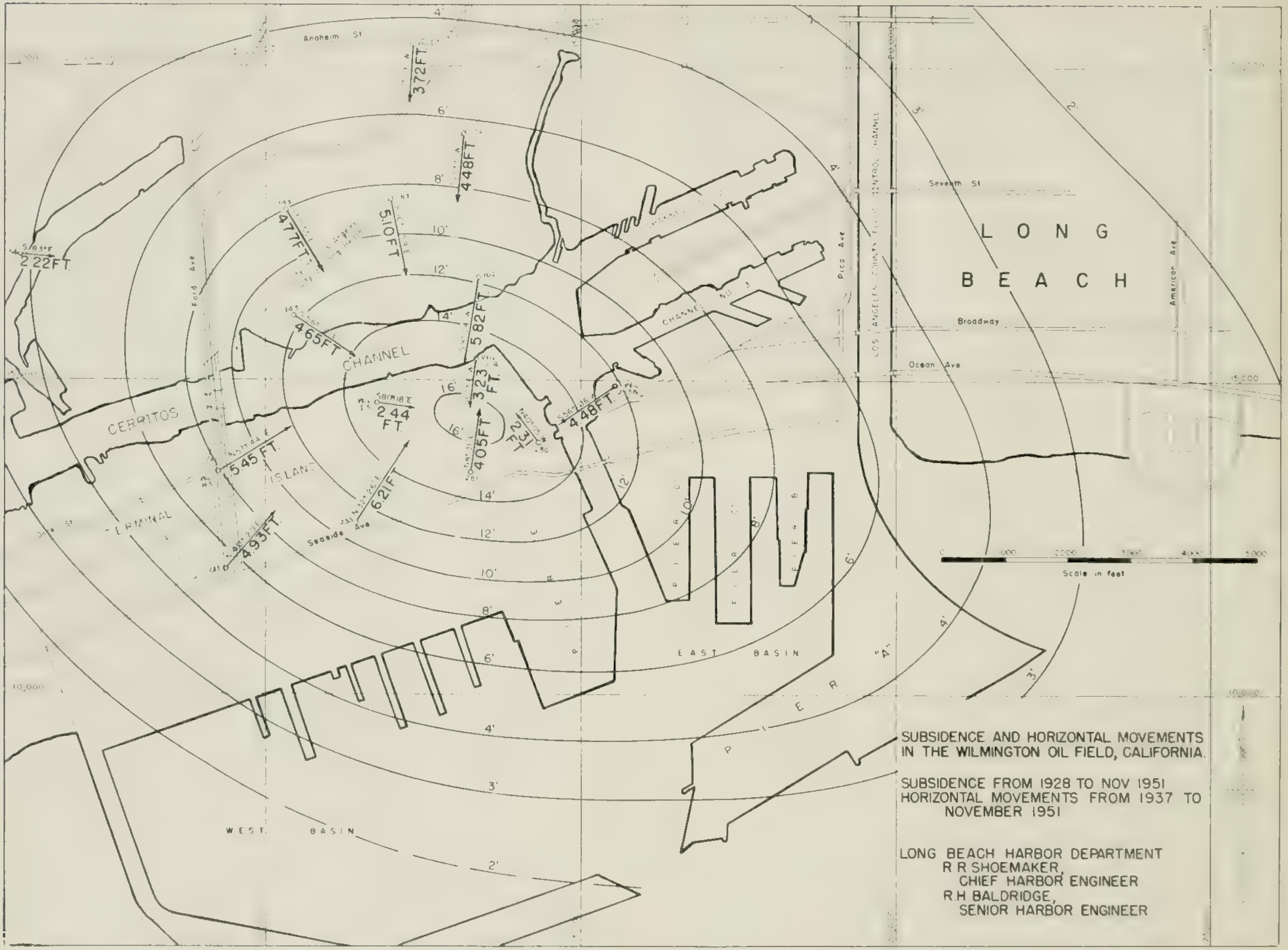

FIGURE 1. Map of Wilmington oil field, showing total subsidence and horizontal movements to November, 1951. *Data chiefly from surveys by Long Beach Harbor Department and Office of Los Angeles County Surveyor and Engineer.*

curve, separating an inner concave surface from an outer annular convex surface; it should be noted that the clamping entirely misrepresents the magnitude and distribution of the internal stresses in the annular outer portion of the prototype. If we confine our interest, at least initially, to the plate within the inflection line, this clamped subterfuge is a very convenient simplification, and serves to explain the nature or the mechanics of some of the phenomena encountered in the oil field.

The assumption that the plate (prism of sediments overlying the Terminal zone in the prototype) is homogeneous and elastically isotropic, and that the constraint against horizontal deflection on the lower surface (where, in the prototype, the overburden rests on the top of the Terminal zone) does not significantly destroy the phenomenon of pure bending, does permit the use of some simple equations developed in the theory of elasticity to explain many of the known facts in the oil field. As the vertical deflection is very small with respect to the lateral extent of the plate, it is reasonable to assume that stress values tangential to isopleths of vertical deflection are so small compared to radial stress values that they can be ignored. This permits the use of the analogue of a horizontal beam of uniform rectangular cross section with built-in ends deformed by a point load or a uniformly distributed load. We can assume that the analogue beam has unit thickness and a depth of section equal to the thickness of the overburden of sediments resting on the Terminal zone. This hypothetical beam is oriented across a diameter of an assumed circular subsidence or, in the more realistic case of an elliptical subsidence, along a line orthogonal to the isobases of subsidence. Torsional stresses must be ignored (Grant, 1954).

With the adoption of these assumptions, we can see from figure 2 that horizontal displacements result from rotation of imaginary planes cutting the long axis of the beams. We can further see that rotation is greatest at the inflection point in the deformation curve, and that no rotation and hence no horizontal displacement occurs at the center of the depression nor at the clamped terminal ends. The equation for the deflection curve of such a clamped beam deformed by a uniformly distributed load is

$$w = Wo \left(1 - \frac{r^2}{a^2}\right)^2 .$$

where w is the vertical deflection of any point (positive downwards), Wo is the maximum vertical deflection at the center, r is the distance along the length of the beam of any particular point measured from the center, and a is the half-length of the beam (Timoshenko, 1940.)* The obvious boundary and center conditions are satisfied by this equation. Differentiating w twice with respect to r and equating to zero demonstrates that the inflection point r_1 is

$$r_1 = \pm \frac{a}{\sqrt{3}} .$$

At the inflection point, where the central concave surface curve merges into the marginal convex curve, the subsidence slope is greatest and the rotation of vertical planes is likewise greatest. Hence, in the prototype, surface points at the inflection line should show the greatest horizontal displacement. Field surveys indicate this to be true. Some survey stations near the inflection line have been displaced more than 6 feet toward the center of the subsided area (fig. 1). It can be readily seen that the amount of horizontal displacement, u, is a function of the magnitude of the rotation angle θ, and of h, the half-depth of the beam (or prism of sediments). Thus,

$$u = f(\theta, h).$$

Because θ is very small, sine θ is approximately equal to tangent θ, and we obtain the relation:

$$u = h \tan \theta .$$

It must be recognized that the simplifying assumptions resorted to above prevent a rigorous analysis, but we can nevertheless apply this simple mechanism and technique to compute the approximate horizontal displacements of surface points if the rotation angle and the thickness of the deformed overburden are known. The rotation angle, θ, is nearly equal to the slope created by subsidence if we neglect the effect of the bottom surface constraint. The slope angle can be readily determined from data on the subsidence maps.

Because the artificiality of an analogue plate or beam with clamped ends destroys the values and distribution of stresses from the inflection point to the clamped margins, it is desirable to eliminate this clamping subterfuge. This can be done by comparing the cross section of the subsided prism of sediments to a beam of infinite

---

* Here we find

$$w = \frac{q}{64D} (a^2 - r^2)^2, \text{ which is equal to}$$

$$w = \frac{qa^4}{64D} \left(1 - \frac{r^2}{a^2}\right)^2 ; \text{ and hence}$$

$$w = Wo \left(1 - \frac{r^2}{a^2}\right)^2 .$$

The q is the intensity of the continuously distributed load and D is the flexural rigidity of the plate. This equation for a thin plate is identical with the equation for the clamped beam.

length resting on an elastic foundation and deformed by a point load. This analogue has the further advantage that it explains the occasional slight uplifts around the margins of the subsiding area. These ephemeral uplifts have been detected in the Wilmington field by repeated spirit leveling. Unfortunately, an adequate mathematical discussion of the deformation of the infinite beam is too lengthy to be included here, but derivations and solutions of the fundamental equations can be obtained from available literature (for example, von Karman and Biot, 1940; Pipes, 1946). The surface curve of such a beam is characterized by a prominent central depression that is bounded outwardly by a small elevation, beyond which are die-away waves somewhat like damped sine curves that become asymptotic to the line of zero ordinate. A marginal annular uplift occasionally detected in the Wilmington field, and also noted in another oil field studied by the author, is likely to be nearly or entirely obliterated periodically by a decrease in flexural rigidity of the deformed strata through shear ruptures, plastic flow, or elastic fatigue.

Subsurface Shear Ruptures. In 1947 a number of oil wells in the Wilmington field were seriously damaged by horizontal shear stresses at depths of about 1,500 to 1,600 feet. These damaged wells are on the strongly flexed south flank of the subsidence in a reniform area bisected by the inflection line. The subsidence slope, and hence the rotation angle of the bent overburden, was greatest in this area. As rotation angles increased with the progress of differential subsidence, several later episodes of subsurface shear damage to wells occurred. Finally, in an area along the inflection line on the north flank of the subsidence, where rotation angles reached critical values at a later date, considerable subsurface shear damage took place. The comparison of shear stresses in deformed beams of uniform cross section provides a crude analogue to the oil field prototype. It can be shown by a mathematical demonstration that, when reasonable simplifying assumptions are made, the axially directed shear stresses in deformed beams are greatest at the inflection points and in the neutral plane of the beam. The neutral plane is midway of the vertical dimensions of the beam. In rock strata, which have less strength in tension than in compression, the neutral plane tends to migrate toward the concave surface during strong bending. The sheared wells were centered about the inflection line, and the shearing damage occurred at points about half way from the surface to the top of the Terminal zone.

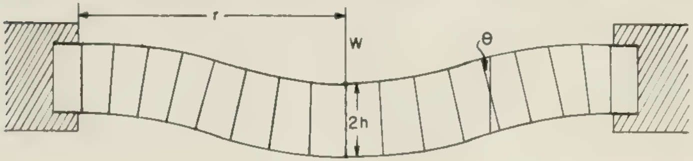

Fig. 2

Figure 2. Vertical deflection of a built-in beam or cross-section of a circular plate with clamped margins, deformed by a center-point load or a uniformly distributed load. The vertical deflection is greatly exaggerated. Note the rotation of vertical planes, greatest at the inflection point in the deformation curve.

It is of interest to note that local earthquakes were caused by some of the sudden shear slips (fault movements) in the Wilmington field.

Shearing Resistance and Drag at Base of Overburden. The plate or prism of sedimentary overburden resting on the top of the Terminal oil zone rotates during the bending (folding) that accompanies differential subsidence. Pure and simple bending is prevented by a constraint against horizontal slipping between the bottom of the overburden plate and the top of the underlying Terminal zone. This is due to the shearing resistance at the contact. Shearing resistance, S_R, can be expressed by the following modification of Coloumb's equation:

$$S_R = C + (P_t - P_u) \tan \phi.$$

where C is cohesion, P_t is normal pressure at the zone of potential rupture due to the total weight of the overburden, P_u is pore-water pressure or hydrostatic pressure in the interstitial fluids, and ϕ is the angle of internal friction of the sedimentary material. Cohesion in uncemented sands normally is lower than in shales, some of which in the Wilmington field are moderately cemented. However, the angle of internal friction in the sands is likely to be much higher than in the shales. The value of ϕ in sands is likely to lie between 30° and 45°, whereas in shales the value generally lies between 12° and 30°. Therefore the resisting shear is likely to be significantly less in the shales than in the sands, and consequently a rupture with horizontal displacement is more expectable in the shales just above the sandy oil beds than in the oil sands themselves.

A glance at the shearing-resistance equation indicates that a reduction in fluid pressure (P_u) greatly increases resisting shear, and it is obvious that oil production reduces reservoir pressure much more rapidly in the producing sands than in the relatively impermeable shales overlying them. Resisting shear may prevent rupture and lateral displacement entirely, in which case the shearing stress merely will distort the sediments in a manner analogous to drag near a fault surface. This drag may be sufficient to bend oil well casings to a degree sufficient to prevent tools passing freely through these parts of the wells.

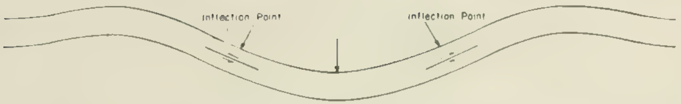

Fig 3

FIGURE 3. Vertical deflection caused by a point load on a beam of infinite length resting on an elastic foundation. Note the marginal uplifts and shearing displacements in the neutral plane at the inflection points.

In some fields, sand produced along with the oil may result in a dilated condition of the oil sand similar to that in quicksand. In this situation cohesion and the coefficient of internal friction (tan ϕ) attain zero values, and a shear rupture and displacement may occur at or near the top of the producing sands. This has been noted by the author in another subsided oil field, where much sand has accompanied the oil during production. In the Wilmington field little sand is produced with the oil, and no actual rupture at the top of the Terminal zone has yet been noted. This particular horizon, however, must be a locus of above-average intensity of shear stress, and a future rupture may occur there if bending of the overburden becomes more severe.

Compression and Tension at the Surface. An inspection of figure 2 demonstrates that radial compression at the surface must result from rotations within the inflection lines, and that radial tension at the surface must occur in an annular area outside the inflection lines. This must follow if the kinematics of deformation of the prototype are like those of the analogue. That the strains in the analogue are representative of those in the prototype is borne out by the buckling of railroad tracks and compression rupture of rigid structures in the central area of subsidence, and by the tension rupture of radially directed linear structures in the outer marginal zone. These strains and failures in the oil field have been very costly.

Vertical Tension in the Center of Subsidence. In 1952 the author's attention was called to what appeared to be tension damage to oil well casings within the overburden sediments in the central portion of the subsidence. In this central area the upper half of the sediments overlying the Terminal zone is subjected to strong radial compression due to centripetal movements of surface points. This horizontal compression must result in a tendency toward vertical expansion, and, as there is not room for much expansion downward, the surface must undergo a relative vertical uplift. This rising of the surface in the central area must be relative and not absolute, as the rate of subsidence there is about 2 feet per year.

Repeated spirit leveling has brought to light a pulsating rate of subsidence, and when the interval between surveys is very short (two weeks) occasional small uplifts have been detected. This phenomenon may be due to irregular periodic upward expansions. The amount of this vertical expansion must be a function of the magnitude of the compressive stresses, the volume of compressed sediments, and the value of Poisson's ratio. This value must be somewhat between zero and one half. We are assuming here that the phenomenon is an elastic one, though unquestionably a part of it must be of a plastic type. Regardless of the relative roles of elasticity and plasticity, the vertical expansion at times has been sufficient to cause tension failures in oil wells.

Threshold Value of Vertical Stress Causing Surface Subsidence. Some oil fields that have been producing for many years either do not seem to have suffered much surface subsidence, or for some reason their subsidence has not become generally known. The compression of aquifers accompanying relatively moderate pressure drops is well known, and it seems reasonable to suppose that reduction in reservoir pressure in all oil fields producing from interstitial voids in granular media must cause some subsidence of the surface. This difference in the magnitude of surface subsidence in oil fields can be due to several factors, of which some are quite obvious and others are obscure. For example, when a thick prism of overburden sediments of high flexural rigidity overlies a localized region of reservoir-pressure drop, the surface subsidence may be inconsequental. In other areas the supporting-arch effect of an anticlinal structure may minimize surface subsidence.

A less obvious factor in minimizing surface subsidence of a producing field is involved in the geologic history of the area. Unconformities in the overburden may represent removal of former thicknesses of sediment whose great weight at one time so compressed the producing zones that additional compression of significant amount cannot be attained even by a reduction of interstitial fluid pressure to atmospheric pressure. Or a threshold value of overburden weight, established by the great sediment thickness that at one time overlay the oil zone, may result in insignificant subsidence during the early producing history of the field—this early slight subsidence being due to elastic strain in the producing zone—whereas later on a critical value of compression is attained and pronounced subsidence occurs. This acceleration of subsidence begins at a definite reduced value of reservoir pressure. Thus a sudden increase in subsidence rate without a parallel sudden decrease in reservoir pressure (due say, to stepped-up production) may lead to detection of obscure disconformities in the overlying sedimentary cover.

It is obvious that subsidence assists oil recovery by tending to maintain reservoir pressure. During subsidence the potential energy of the overlying prism is converted in part into reservoir energy.

Concluding Note. The foregoing abbreviated and elementary analysis of the known physical facts accompanying subsidence in the Wilmington field demonstrates in a nonrigorous manner the mechanics of this phenomenon. The author accepts responsibility for this inelegant treatment of the subject, but he is indebted to his colleague, Professor Louis A. Pipes of the Engineering School, University of California at Los Angeles, for much assistance and advice, and to Messrs. R. R. Shoemaker, Chief Harbor Engineer, Frank Hardesty, Chief Petroleum Engineer, Charles L. Vickers, Chief Civil Engineer, and Roy H. Baldridge, Senior Harbor Engineer, Long Beach Harbor Department, for supplying data and in every way facilitating the study. The author also has been aided by discussions with Messrs. J. Herbert Davies and William H. Cooke, of the J. H. Davies Engineers, Long Beach, California.

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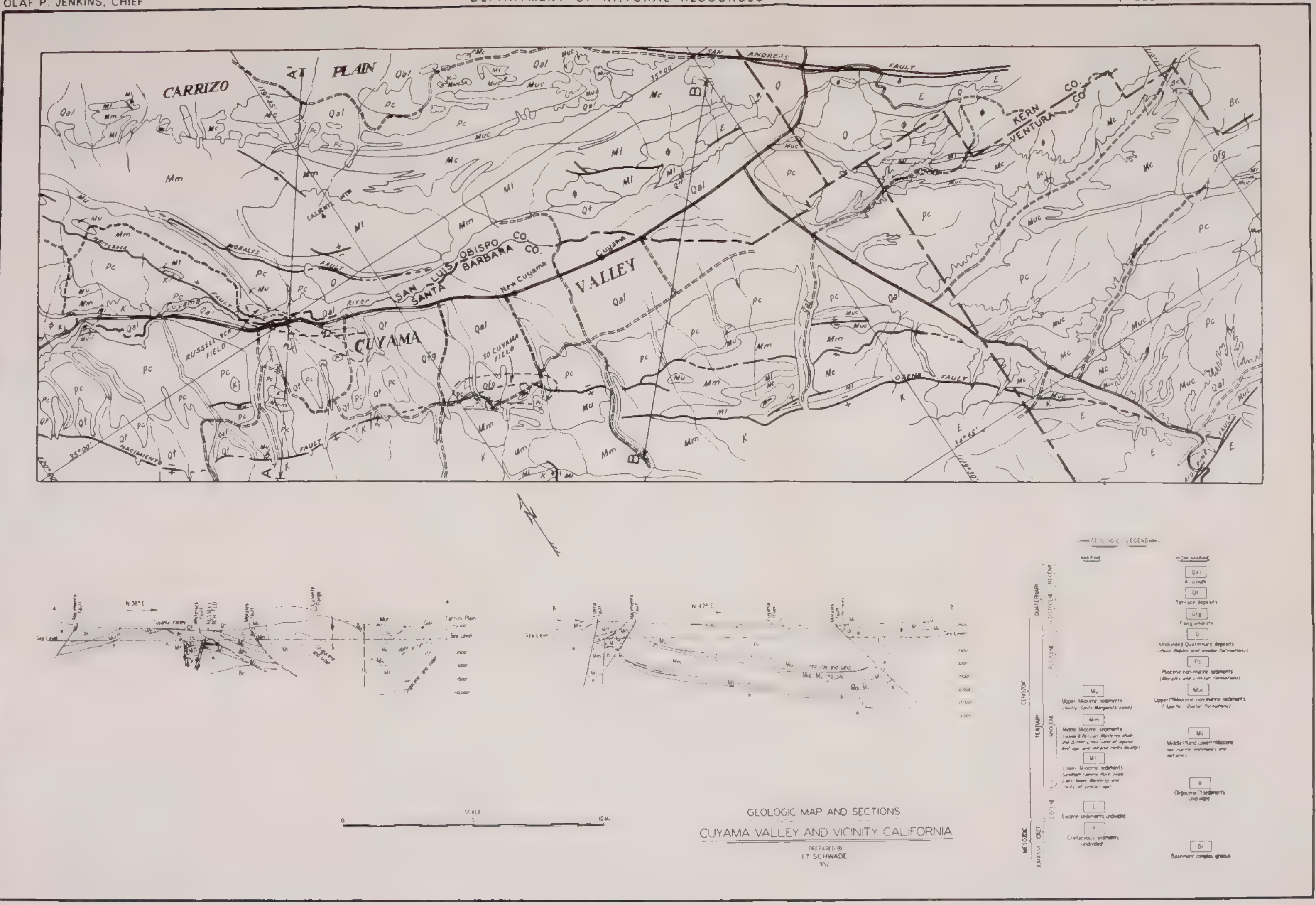
CARRIZO PLAIN
CUYAMA VALLEY
SAN LUIS OBISPO CO.
SANTA BARBARA CO.
KERN CO.
VENTURA CO.
SAN ANDREAS FAULT
MORALES FAULT
OZENA FAULT
NACIMIENTO FAULT
RUSSELL RCH FIELD
SO CUYAMA FIELD
New Cuyama
River
35°00'
Qal
Qt
Qfg
Q
Pc
Muc
Mc
Mu
Mm
Ml
E
K
Bc
A
B
Sea Level
GEOLOGIC LEGEND
MARINE
NON MARINE
QUATERNARY
TERTIARY
CENOZOIC
MESOZOIC
RECENT
PLEISTOCENE
PLIOCENE
MIOCENE
EOCENE
CRET.
JURASSIC
Qal Alluvium
Qt Terrace deposits
Qfg Fanglomerate
Q Undivided Quaternary deposits (Paso Robles and similar formations)
Pc Pliocene non-marine sediments (Morales and similar formations)
Mu Upper Miocene sediments (chiefly Santa Margarita sand)
Muc Upper (?) Miocene non-marine sediments (Apache "Quatal" formations)
Mm Middle Miocene sediments
Mc Middle (?) and Lower (?) Miocene non-marine sediments
Ml Lower Miocene sediments
O Oligocene (?) sediments undivided
E Eocene sediments undivided
K Cretaceous sediments undivided
Bc Basement complex, granite
SCALE
0
10 MI.

GEOLOGIC MAP AND SECTIONS
CUYAMA VALLEY AND VICINITY CALIFORNIA
PREPARED BY
I.T. SCHWADE

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 1

GEOLOGY OF CUYAMA VALLEY AND ADJACENT RANGES, SAN LUIS OBISPO, SANTA BARBARA, KERN, AND VENTURA COUNTIES

By Irving T. Schwade *

Introduction. Cuyama Valley, an intermontane basin about 50 miles long and 8 miles wide, lies near the boundary of eastern San Luis Obispo and Santa Barbara Counties and adjacent Kern and Ventura Counties. It is bordered on the north and south by imbricate thrust blocks which have overridden younger rocks at the edges of the valley. This graben has a central transverse downwarped area that lies between a considerably elevated granitic terrane at Mount Pinos on the eastern end and masses of Cretaceous strata on the west (see map). Total relief within the graben, between the deepest part along the northern valley border northeast of the town of Cuyama and outcrops of basement rocks, is more than 20,000 feet. Maximum relief along the bordering faults is about 15,000 feet on the north (Whiterock and Morales thrust displacements) and about 10,000 feet on the south (Nacimiento and Ozena fault displacements). All oil production, which dates from 1948, is confined to the graben block.

Stratigraphy. The Tertiary stratigraphic section of Cuyama Valley is shown on the accompanying geologic legend. The Pliocene Morales formation comprises buff to tan clays, sands, and conglomerates. In the subsurface a considerable local lacustrine clay facies is suggested, along with the possibility of a number of local unconformities.

The Miocene sediments in the valley exhibit a systematic variation from marine on the west to nonmarine on the east. Upper Miocene marine sediments, locally called Santa Margarita, are chiefly sandstones with subordinate olive brown clayey siltstones. These beds are best seen in outcrop immediately east of Whiterock Bluff, where they unconformably underlie Morales clays and conformably overlie middle Miocene siliceous shales. Eastward, in the subsurface beneath the valley proper, Santa Margarita sandstones interfinger with redbeds, and in the eastern part of the valley, the marine facies is absent and the formation consists chiefly of bentonitic, structureless red claystones, with minor sandstone beds, probably largely of lacustrine origin. In this area it is called Quatal formation, and is best seen in exposures east of the Cuyama-Ventura highway a few miles north of the Big Pine fault.

Middle Miocene sediments exhibit a considerable lateral variation both in outcrop and subsurface. The westernmost exposures of middle Miocene strata shown on the accompanying map are entirely Monterey shale, chiefly siliceous; however, in the subsurface a short distance to the east the first fingers of sandstone, locally called Bitter Creek, have been noted. Largely at the expense of the shales, but in addition with each unit exhibiting considerable thickening, the sandstones become the dominant sedimentary feature of the middle Miocene section in the central part of Cuyama Valley and in the hills to the south. On the north side of Caliente Mountain the Bitter Creek forms a prominent part of the middle Miocene section, but less dominantly so than in the area to the south. This unit, made up chiefly of fine, silty, locally cross-bedded, fossiliferous sandstone, is considered to represent a large middle Miocene delta built up of sediments derived from the land area to the east. To the east, Bitter Creek beds interfinger with, and progressively grade into, terrestrial conglomerates and redbeds, locally called the Caliente formation. The Caliente formation is best exposed in the southeastern part of the valley in proximity to the upper (?) Miocene nonmarine strata described above

Lower Miocene sediments exhibit considerable variations in thickness over most of the valley, but except in the outcrop area at its eastern end, where equivalent beds probably are in part terrestrial, the formation is entirely marine. In the productive area the lower Miocene section consists of 200 to 250 feet of clay shale; 450 to 650 feet of fine to coarse permeable sandstone and subordinate shale breaks, the productive portion of which is locally known as Dibblee zone of the Painted Rock formation; a lower shale, 200 to 350 feet thick, known as Colgrove shale; and a basal productive sandstone, known as Colgrove sand in the Russell Ranch field and Hibberd sand in the South Cuyama field, about 50 to 100 feet thick. To the northeast, in the hanging-wall block along the Morales fault, the Painted Rock formation reaches an aggregate thickness of about 5,000 feet, and consists of more than 50 percent of sandstone; here the oil-field equivalents of the Painted Rock formation are indistinguishable. To the east, in central Cuyama Valley, the formation is not as clear-cut as in the productive areas, except faunally; the shale-sandstone boundaries are variable, and the sandstones commonly are highly indurated. Only a few hundred feet of lowest Miocene marine beds is visible in outcrop at the eastern margin of the valley, where the beds are overlain by Caliente nonmarine beds and underlain by Oligocene (?) beds.

Oligocene (?) sediments, known as the Simmler formation, are visible on the northeastern and eastern valley margins; in the former area they consist of dense, reddish-chocolate clay shales and hard, reddish-brown sandstones, and in the latter area they consist of fanglomerates with abundant diorite boulders in a matrix of red shale and sandstone. Strata that are lithologically similar to the Sespe formation of the Ventura basin have been encountered in several wells in the northern and western valley area.

Eocene strata are present in outcrop in the southeastern portion of the San Rafael homocline, in the eastern Caliente Range, in the eastern Cuyama Valley immediately west of the San Andreas fault, and in the subsurface of the area northeast of the Ozena fault and north of the Big Pine fault. The formation consists chiefly of marine shales and subordinate poorly sorted sandstones, both commonly very hard. No Eocene rocks have been identified in or near the productive area.

Dark gray shale of Paleocene age has been encountered in a few deep wells about 4 miles northwest of the Russell Ranch field.

Strata tentatively identified as Cretaceous, mainly by inference and by means of a few nondiagnostic microfossils, consist of interbedded dense, dark gray shales, hard gray sandstones, and a lower granite- and quartzite-boulder conglomerate above granitic basement rocks.

Structure. The Cuyama Valley area can be divided into three principal structural units: (1) Cuyama graben, (2) Caliente uplift on the north, and (3) San Rafael uplift on the south.

The Cuyama graben is a complex dual basin with a central transverse structural ridge and upwarped east and west flanks. The eastern basin is a northward-plunging structural depression whose lowest point lies a few miles east of the town of Cuyama along the northern valley border, where it has been overridden by the Caliente uplift along what is probably the eastern extension of the Morales fault. The western basin, considerably shallower and plunging southward, lies on the southwest flank of the exposed Cretaceous section a few miles west of the Russell Ranch field. These Cretaceous outcrops mark the position of the crudely defined northward-striking ridge that separates the above basins. The Russell Ranch field lies on the east flank of this ridge; updip closure is achieved by a series of closely spaced westward-dipping normal faults. The South Cuyama field is a domal structure probably related to the median ridge described above, with complex (probably chiefly strike-slip) faulting on the southwest flank. The faults described along the field edges are unknown in outcrop; however, the strike and character of this faulting in a moderately broad zone on similar parts of two fields that have a rough alignment, suggest that a single system of faulting, known as the Russell fault, is continuous between the hanging-wall overriding blocks of the Nacimiento and Whiterock faults.

The Caliente anticlinal uplift, which lies on the hanging-wall side of the roughly parallel and doubtless closely related Whiterock and Morales faults, has a westerly regional plunge, and exposes progressively older rocks down to Eocene eastward in the cores of a number of en-echelon closed anticlines superimposed on the uplift. The largest of these features is the Caliente dome, which exposes lower Miocene rocks in its core. Information derived from subsurface rocks, however, suggests that this feature terminates downward at the faulting which limits this tectonic block.

The San Rafael uplift, terminated northward by the related Nacimiento and Ozena fault systems, is a folded and faulted belt containing chiefly Cretaceous and Eocene sandstones and shales that overlie Franciscan basement rocks and are unconformably overlain by remnants of Miocene strata. In the vicinity of Cuyama valley, on the hanging-wall side of the Nacimiento-Ozena fault system, all exposed Cretaceous and Eocene strata have a homoclinal dip southward into a major regional syncline along the Sisquoc River.

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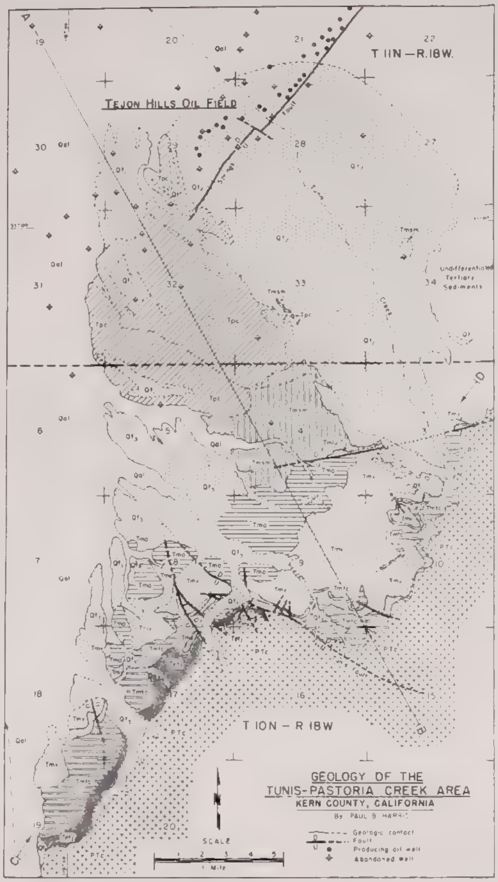
* Geologist, Richfield Oil Corporation, Bakersfield.



COLUMNAR SECTION TUNIS-PASTORIA CREEK AREA

ERA	PERIOD	EPOCH	STAGE	FORMATION	SYMBOL	SECTION	THICKNESS IN FEET	CHARACTER
CENOZOIC	QUATERNARY	RECENT		ALLUVIUM	Qal		0-300'	Soil, sand, and gravel
				TERRACE DEPOSITS POST-TUNIS	Qt 3		0-50'	Boulder and cobble gravel
				TUNIS	Qt 2		0-200'	
				PRE-TUNIS	Qt 1		0-230'	
		PLEISTOCENE (?)					Major Unconformity	
	TERTIARY	LOWER PLIOCENE		CHANAC	Tpc		550-1250'	Continental Tan gritty mudstones, sandstones, conglomerates and claystones ● Green claystones and coarse arkosic sandstones
		UPPER MIOCENE	DELMONTIAN UPPER MOHNIAN	SANTA MARGARITA	Tmsm		300-650' Major Unconformity	● Marine White, coarse, pebbly sandstone, and conglomerates
			LOWER MOHNIAN	PULVINULINELLA GYROIDINAEFORMIS ZONE	Tmlmh		0-600'	● Marine Silty Shales and fine sandstones--subsurface only
		MIDDLE MIOCENE	LUISIAN	VALVULINERIA CALIFORNICA ZONE	Tmlu		0-400'	● Marine Silty shales and fine sandstones--primarily subsurface
			(?)	SIPHOGENERINA BRANNERI ZONE	Tmr		0-75'	Marine Silty shales--subsurface only
			RELIZIAN	OLCESE	Tmo		0-1100' Major Unconformity	● Marine & Continental Coarse, gritty sandstones and boulder conglomerates
		LOWER MIOCENE	SAUCESIAN	VOLCANIC ROCKS	Tmv		0-1500'	Basalt and andesite flows, dacite flows and associated pyroclastics, basalt intrusions
				TECUYA	Tmtc		0-1090' Major Unconformity	● Marine & Continental Conglomerates, coarse arkosic sandstones, fine sandstones and silts
		UPPER EOCENE	A-3	TEJON	[illegible]		0-410' Major Unconformity	Marine Tan, fine sandstone, silt, sandstone, conglomerate, fossil and calcareous reefs
PRE-TERTIARY				CRYSTALLINE ROCKS	PTc			Granodiorite, gneiss, schist, quartzite, and coarsely crystalline marble

● PRODUCES OIL IN OR ADJACENT TO AREA

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GEOLOGY OF SOUTHERN CALIFORNIA

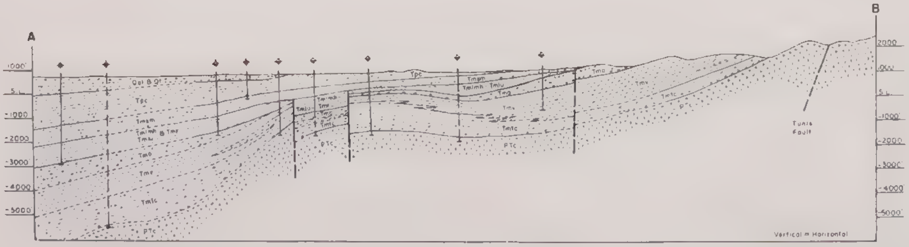
MAP SHEET NO. 2

GEOLOGY OF THE TUNIS-PASTORIA CREEK AREA, KERN COUNTY

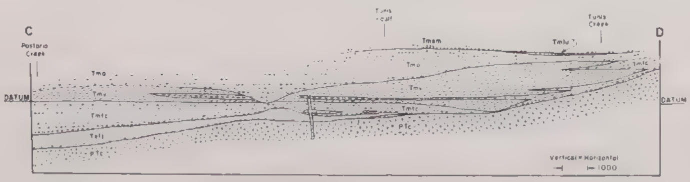
By Paul B. Harris*

The geology of the Tunis-Pastoria Creek area, located approximately thirty miles southeast of Bakersfield, California, is rather simple from a regional standpoint. It more closely resembles the geology of the eastern edge of the San Joaquin Valley than that of the Coast Range province to the west. In the area mapped, pre-Tertiary crystalline rocks of the Tehachapi Mountains are overlain with a depositional contact by Tertiary sedimentary and volcanic rocks. These Tertiary rocks range in age from upper Eocene to lower Pliocene, and attain a thickness of approximately 5500 feet. Extensive terrace deposits and tilted alluvial fans of Quaternary age record the more recent history of this part of the San Joaquin Valley.

Structurally the area is characterized by strata that dip moderately to the northwest, and by a radial system of nearly vertical faults. Most of the faults are believed to be of the normal type. Subsurface data indicate that recent displacement along the Springs fault, which offsets Recent alluvial gravels, has been opposite in direction to that of previous major movements. Folding is minor and limited primarily to phenomena associated with faulting. Structures have been complicated by repeated periods of uplift and subsidence that have given rise to numerous unconformities in the Tertiary section.



NORTHWEST – SOUTHEAST CROSS SECTION AB



DIAGRAMMATIC SOUTHWEST – NORTHEAST SECTION CD

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* Geologist, The Texas Company, Sacramento.

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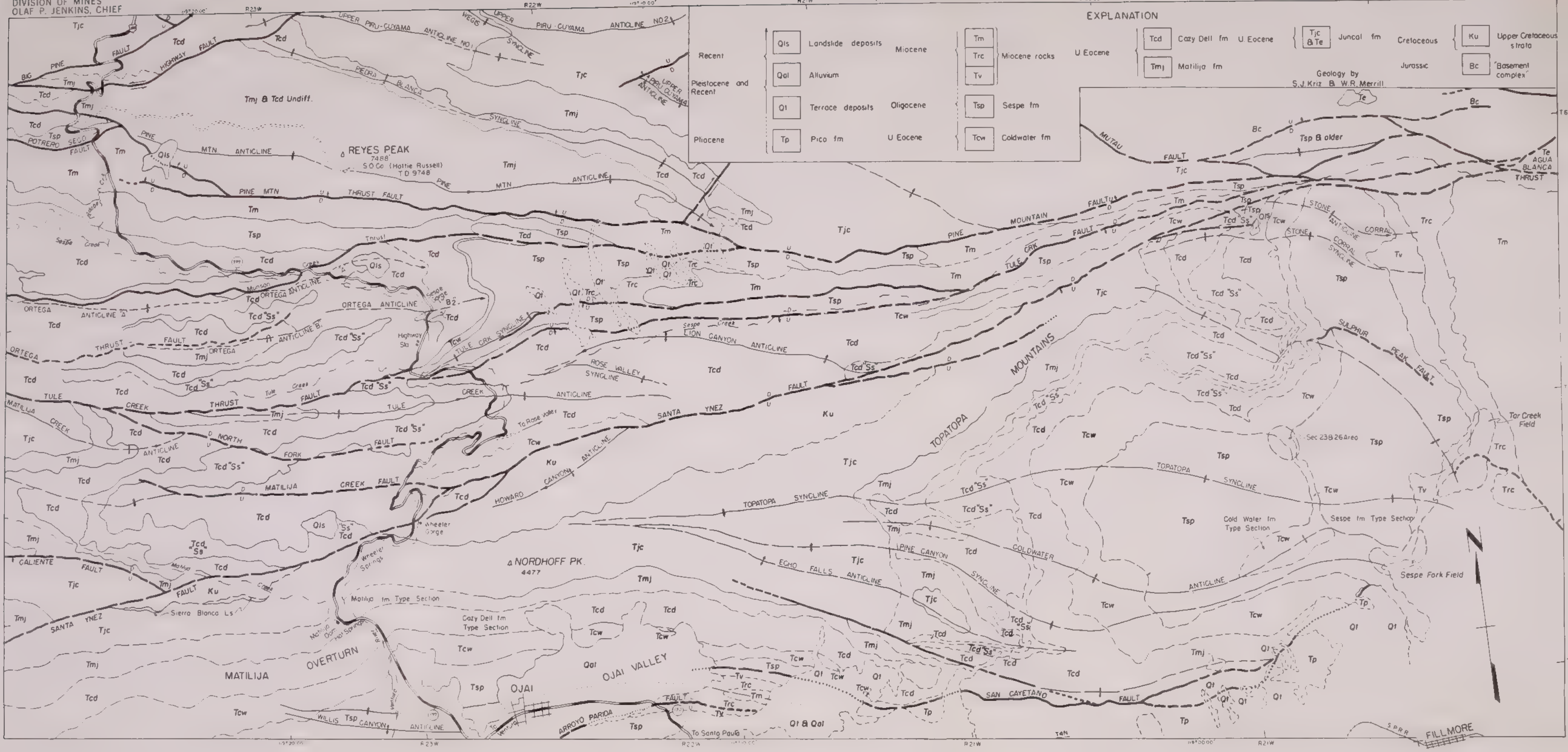
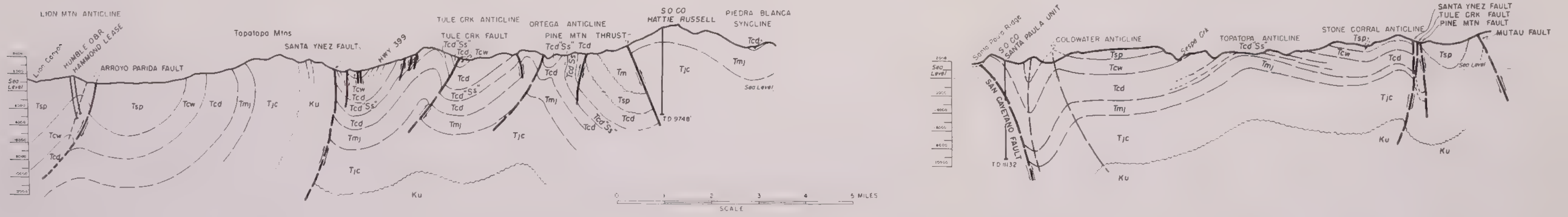
BULLETIN 170 MAP SHEET 3





DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 3

GEOLOGY OF THE SESPE CREEK-PINE MOUNTAIN AREA, VENTURA COUNTY

By William R. Merrill *

The area shown on the accompanying geologic map lies within the Transverse Range province, and includes the western ends of both the Santa Ynez and San Rafael Mountains. Altitudes range from about 450 feet in the Santa Clara River Valley near the town of Fillmore to 7,488 feet at Reyes Peak. The rocks and geologic structure are well exposed on the numerous rugged slopes and canyon walls of the area.

More than 22,000 feet of sedimentary section is present, and the stratified rocks range in age from middle Miocene to Upper Cretaceous. A basement complex, composed of intrusive igneous rocks, volcanic rocks, and metamorphic rocks, crops out in the northeast corner of the map area, where it is in fault contact with the sedimentary section. Franciscan and Knoxville (Jurassic-Lower Cretaceous) rocks crop out to the northwest beyond the map area, and are believed to be at depth within the map area. Approximately 5,000 feet of Upper Cretaceous sandstones, conglomerates, siltstones, and hard, dark, splintery shales has been measured along the south side of the Santa Ynez fault. The base of the Cretaceous section is not exposed within the map area.

Disconformably overlying the Cretaceous strata is approximately 3,200 feet of sediments determined to be late Eocene in age. This Eocene section has been divided into the Coldwater (2,000 feet thick), Cozy Dell (3,800 feet), Matilija (2,450 feet), and Juncal (5,000 feet) formations of current usage. The Sierra Blanca limestone unit occurs discontinuously at the base of the Juncal. The Coldwater and Matilija formations are similar, and are composed of hard, arkosic sands. The Cozy Dell and Juncal formations are composed of siltstones and clay shales. Although a considerable hiatus apparently is represented between this upper Eocene section and the underlying Upper Cretaceous strata, fossil control is necessary for the selection of the contact wherever the Sierra Blanca limestone is absent.

The Sespe formation, 4,500 feet in maximum thickness, conformably overlies the Coldwater along the south and east within the map area. To the northeast, however, the Sespe progressively overlaps the Coldwater and rests directly upon the Cozy Dell formation. The Sespe formation is nonmarine, and is composed of red and varicolored sandstones, conglomerates, siltstones, and clay shales. Conformably overlying the Sespe along the south edge of the map area is the Vaqueros formation, of early Miocene age. To the north and east the Vaqueros and progressively younger Miocene strata lap out against older and older sediments, until in the northeast corner of the map area middle Miocene beds lie directly upon Sespe beds. This relationship continues to the northeast beyond the map area, until upper Miocene sediments are found to lie directly upon Knoxville and Franciscan rocks.

Type sections for the Sespe, Coldwater, Cozy Dell, and Matilija formations have been noted on the accompanying geologic map. The type section for the Juncal formation lies in the area immediately to the west of that shown on the map. Structurally the map area represents a part of a regional anticlinal nose, which is in a sense an anticlinorum. The core of this structure lies to the northwest, in the San Rafael Mountains, and dissipates eastward and down-plunge in the Castaic-Newhall area. The south flank of this large fold is truncated by the Santa Ynez fault, which has structurally elevated the rocks on the south side. To the north the Pine Mountain fault sets off a third block, so that the central portion of the map area is a block that has been down-dropped. This central block has been severely folded, particularly in the vicinity of the Santa Ynez and Tule Creek faults, where many of the folds have overturned flanks. Farther to the south, the entire section, including 15,000 feet or more of upper Eocene and Oligocene beds, has been overturned along a strike distance of 20 miles or more (Matilija overturn). The Santa Ynez and other related faults also have been overturned in this area.

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* Geologist, Standard Oil Company of California, Los Angeles.

COLLATE:

34 PIECES

CONTENTS: MAP SHEETS 1-34

1. Geology of Cuyama Valley and adjacent ranges, San Luis Obispo, Santa Barbara, Kern, and Ventura Counties.
2. Geology of the Tunis-Pastoria Creek area, Kern County.
3. Geology of the Sespe Creek-Pine Mountain area, Ventura County.
4. Geology of the western Ventura basin, Santa Barbara, Ventura, and Los Angeles Counties.
5. Geology of part of the eastern Ventura basin, Los Angeles County.
6. Geology of the Soledad basin, Los Angeles County.
7. Geology of the Ridge Basin area, Los Angeles and Ventura Counties.
8. Geology of the Santa Monica Mountains, Los Angeles and Ventura Counties.
9. Geology of the western San Gabriel Mountains, Los Angeles County.
10. Geology of the Little Tujunga area, Los Angeles County.
11. Geologic map of the Owens Valley region, California.
12. Geology of the Talc City area, Inyo County.
13. Geology of the Redrock Canyon-Last Chance Canyon area, Kern County.
14. Geology of the Rosamond Hills, Kern County.
15. Geology of a part of the Shadow Mountains, western San Bernardino County.
16. Geology of the Quail Mountains, San Bernardino County.
17. Geology of the Alexander Hills area, Inyo and San Bernardino Counties.
18. Geology of the Barstow area, San Bernardino County.
19. Geology of the Silurian Hills, San Bernardino County.
20. Geology of the north side of San Gorgonio Pass, Riverside County.
21. Geology of the Corona-Elsinore-Murietta area, Riverside County.
22. A typical portion of the southern California batholith, San Diego County.
23. Geology of the Jacumba area, San Diego and Imperial Counties.
24. Geology of a portion of Joshua Tree National Monument, Riverside County.
25. Geology of the Carpinteria district, Santa Barbara County.
26. Geology of the Rincon oil field, Ventura County.
27. Geology of the San Miguelito oil field, Ventura County.
28. Geology and occurrences of oil in the Ojai-Santa Paula area, Ventura County.
29. Geology of the South Mountain oil field, Ventura County.
30. Geology of the Honor Rancho oil field, Los Angeles County.
31. Geology of the Placerita oil field, Los Angeles County.
32. Geology of the Dominguez oil field, Los Angeles County.
33. Geology of the Wilmington oil field, Los Angeles County.
34. Geology of the Long Beach oil field, Los Angeles County.

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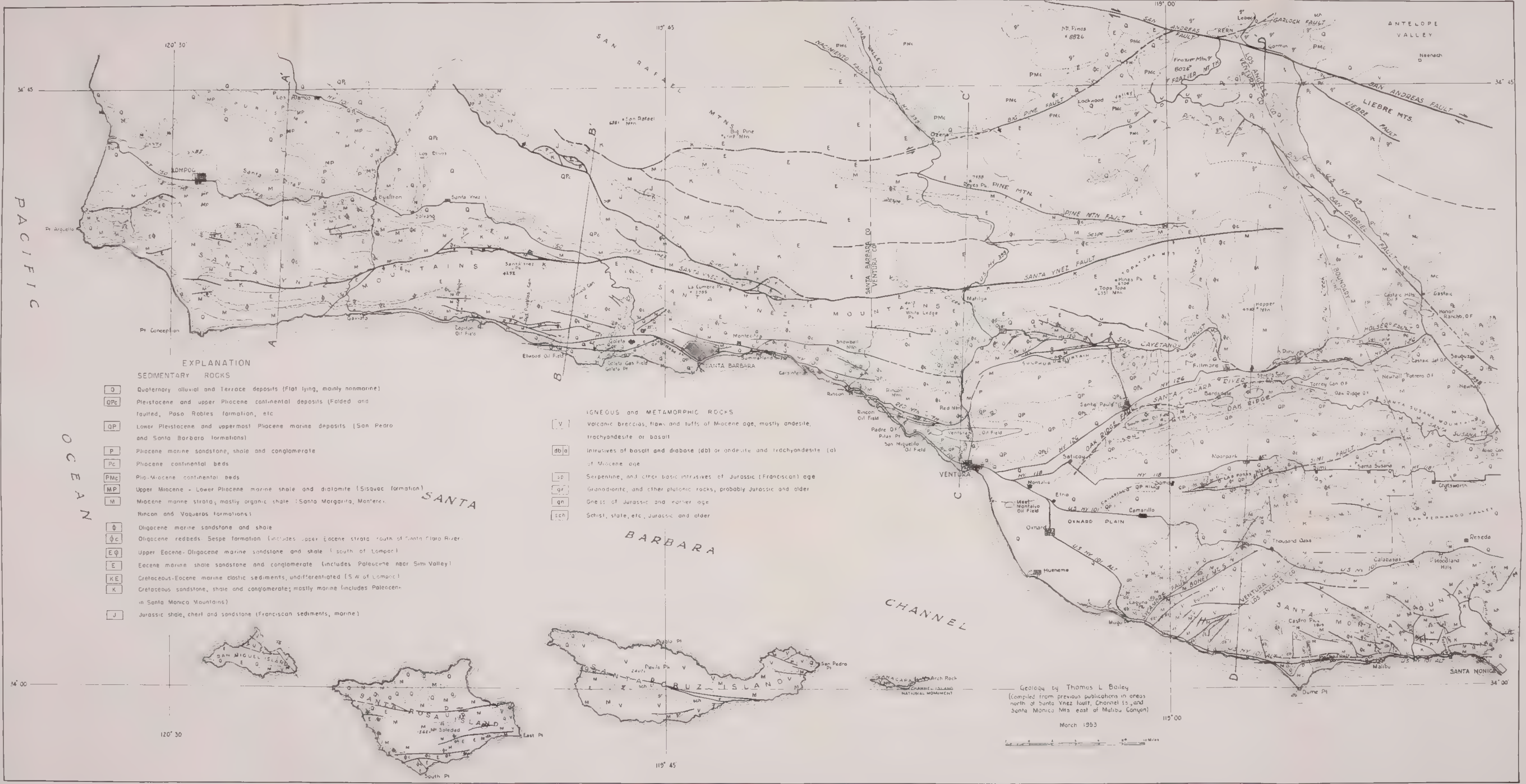
BULLETIN 170 MAP SHEET 4



EXPLANATION

SEDIMENTARY ROCKS

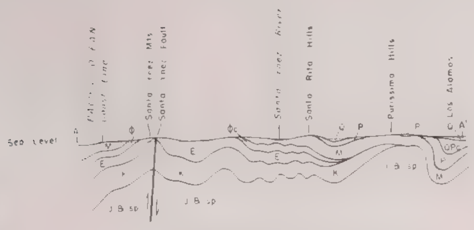
Q	Quaternary alluvial and Terrace deposits (Flat lying, mainly nonmarine)
QPc	Pleistocene and upper Pliocene continental deposits (Folded and faulted, Paso Robles formation, etc
QP	Lower Pleistocene and uppermost Pliocene marine deposits (San Pedro and Santa Barbara formations)
P	Pliocene marine sandstone, shale and conglomerate
Pc	Pliocene continental beds
PMc	Plio-Miocene continental beds
MP	Upper Miocene - Lower Pliocene marine shale and diatomite (Sisquoc formation)
M	Miocene marine strata; mostly organic shale (Santa Margarita, Monterey, Rincon and Vaqueros formations)
Φ	Oligocene marine sandstone and shale
Φc	Oligocene redbeds Sespe formation (includes upper Eocene strata south of Santa Clara River)
EΦ	Upper Eocene-Oligocene marine sandstone and shale (south of Lompoc)
E	Eocene marine shale sandstone and conglomerate (includes Paleocene near Simi Valley)
KE	Cretaceous-Eocene marine clastic sediments, undifferentiated (S W of Lompoc)
K	Cretaceous sandstone, shale and conglomerate; mostly marine (includes Paleocene in Santa Monica Mountains)
J	Jurassic shale, chert and sandstone (Franciscan sediments, marine)

IGNEOUS and METAMORPHIC ROCKS

V	Volcanic breccias, flows and tuffs of Miocene age, mostly andesite, trachyandesite or basalt
db | a	Intrusives of basalt and diabase (db) or andesite and trachyandesite (a) of Miocene age
sp	Serpentine, and other basic intrusives of Jurassic (Franciscan) age
gr	Granodiorite, and other plutonic rocks, probably Jurassic and older
gn	Gneiss of Jurassic and earlier age
sch	Schist, slate, etc, Jurassic and older

Geology by Thomas L Bailey
(Compiled from previous publications in areas north of Santa Ynez fault, Channel Is., and Santa Monica Mts east of Malibu Canyon)

March 1953



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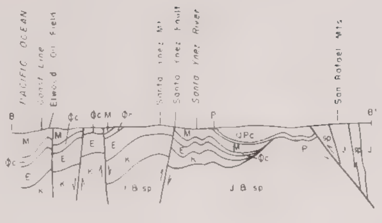

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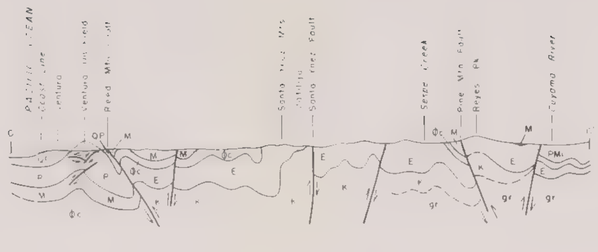

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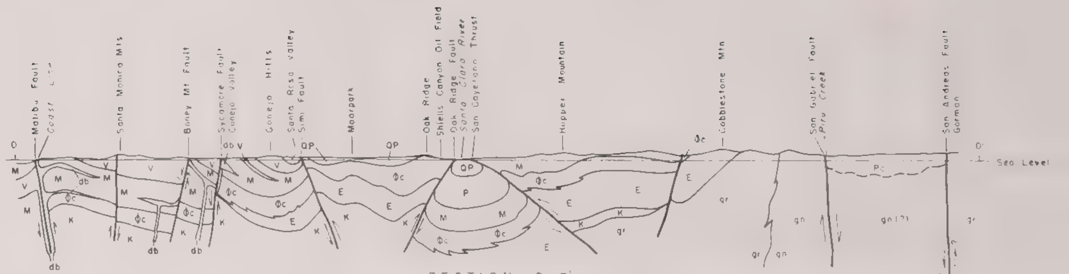

SECTION D-D'

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 4

GEOLOGY OF THE WESTERN VENTURA BASIN, SANTA BARBARA, VENTURA, AND LOS ANGELES COUNTIES

By Thomas L. Bailey *

The accompanying map of the western Ventura basin includes more than three-quarters of the entire basin, which is 120 miles long, 20 to 40 miles wide, and lies about 50 miles northwest of Los Angeles. It covers about the northern half of the western Transverse Range province of southern California. The Ventura basin is a complexly folded and faulted synclinorium lying between the Santa Ynez-Topatopa Mountains on the north and the Santa Monica Mountains and their westerly continuation, the Channel Islands, on the south. The western half of this basin is submerged beneath the shallow waters of the Santa Barbara Channel. The city of Ventura is close to the geographic and depositional center of the basin, where 40,000 to 50,000 feet of Tertiary and Quaternary clastic strata and at least 5,000 feet of Cretaceous clastic strata are preserved. Most of these sedimentry rocks are marine. The central or deepest part of this synclinorium parallels the major stream, the westward flowing Santa Clara River; its axis lies a mile or so north of the river, and passes through or close to the towns of Piru, Fillmore, Santa Paula, and Ventura.

The topography of the area is mostly mountainous or ruggedly hilly. The general altitude of the mountains on the north rim is 2,000 to 6,000 feet, aud on the south rim is 1,000 to 2,500 feet. The basin is traversed by several east-trending intra-basin ridges which attain altitudes of as much as 2,600 feet and are generally anticlinal in structure. Between these ridges are synclinal, depositional plains such Ojai Valley, Santa Clara Valley, and Simi Valley. A recently uplifted delta of the Santa Clara River, the Oxnard Plain, centers near the city of Oxnard. It is the most extensive lowland, and, together with the lower part of the Santa Clara Valley, includes the richest lemon-growing acreage in the United States. The climate is semi-arid, and large volumes of ground-water, mostly derived from Pleistocene sands and gravels, are used in irrigation.

The rocks in the Ventura basin range in age from Recent to Jurassic or Triassic. On the northeast and east the oldest rocks consist of granodiorite and related plutonic types intruded into older gneisses and schists. The south rim of the basin, which crops out in the Santa Monica Mountains and on Santa Cruz Island, is composed of a basement of pre-Cretaceous phyllites and schists that have been locally intruded by diorite and granodiorite. On the north and northwest rim, the basement consists of only slightly metamorphosed Franciscan (Jurassic?) sandstone, shale, and chert that have been extensively intruded by serpentine and other basic igneous rocks, now partly metamorphosed.

From 3,000 to 5,000 feet or more of Cretaceous marine sandstone and shale (mostly Upper Cretaceous) generally rest on the basement rocks, but in the eastern Santa Monica Mountains the Cretaceous section consists mainly of conglomerate, the lower part of which is continental redbeds. Lower Cretaceous rocks are known only near Lompoc and Buellton, at the northwest corner of the basin and north of the Transverse Ranges.

The Ventura basin and associated Transverse Ranges probably began as a fairly broad, east-trending geosynclinal depression or embayment in late middle Eocene time, following an obscure period of moderate uplift and extensive erosion near the end of early Eocene time. This is indicated by the fact that lower Eocene and Paleocene strata are preserved only as remnants, mostly in the Simi Valley region, whereas the middle and upper Eocene marine silty shale and sandstone are extensively preserved on both the north and south margins of the basin, indicating widespread east-west submergence.

Into this rapidly subsiding basin were deposited 5,000 to 8,000 feet of middle Eocene and as much as 9,000 feet of upper Eocene grit, sandstone, and shale. However, by upper Eocene time the southeastern part of the basin had filled up with sediments to points above sea level, and 2,500 feet of continental redbeds that contain an upper Eocene land vertebrate fauna (lower part of the Sespe formation) accumulated in the Simi Valley—Oak Ridge area while marine sedimentation was continuing to the north and west.

During the Oligocene epoch, marine waters progressively retreated to the west end of the basin, and 2,000 to 5,000 feet of land-laid sandstone, siltstone, and conglomerate (Sespe redbeds) accumulated over the entire basin, except for the northwest corner near Lompoc. About the end of Oligocene time or a little later there was a general emergence of the Simi Hills and surrounding area in the southeastern part of the basin, where an angular unconformity, with a strike difference of as much as 90° above and below it, is preserved between Oligocene and middle Miocene strata at the west end of the Simi Hills.

About the beginning of Miocene time, the sea began its greatest easterly advance, transgressing the entire basin and culminating during middle Miocene time with the development of a deep, narrow geosyncline near the site of the present Santa Monica Mountains. An elevated land mass of which Catalina Island is a remnant was rising to the southeast. This land furnished much of the middle Miocene sediment that comprises the 5,000 to 10,000 feet of black shale, sandstone, and lenses of schist-bearing breccia that are now exposed on the southern margin of the Ventura basin. This geosynclinal downwarping was accompanied by submarine outpouring of a large volume of volcanic material of trachyandesitic to basaltic composition with an aggregate thickness of 5,000 feet or more in the Santa Monica Mountains and Channel Islands. The interlayered volcanic and sedimentary rocks have a maximum thickness of at least 15,000 feet in the western Santa Monica Mountains. In late Miocene to middle Pliocene time, recurrent orogenic uplifts folded and faulted up the Santa Monica Mountains and Channel Islands into a mountain range.

A broad epicontinental Miocene sea, subject to slow, fine sedimentation only, occupied the central and northern parts of the western Ventura basin during Miocene time. Laid down in the sea were 2,500 to 4,000 feet of bituminous, laminated, foraminiferal and diatomaceous organic shale and cherty shale, as well as clay shale and a 300-foot basal sand bed, the Vaqueros, in the lower part of the Miocene section. These Miocene organic shales are the richest source rocks for oil and gas.

In late Miocene to middle Pliocene time the south half of the basin (south of the Santa Clara River) was being folded up above sea level to form three low anticlinal ranges of hills, Oak Ridge, Las Posas Hills, and Simi Hills. These hills were largely peneplaned, and were covered with marine waters in late Pliocene and early Pleistocene time, as shown by the fact that upper Pliocene strata rest directly upon Miocene and older rocks in most of this southern area.

Lower and middle Pliocene time was characterized by a narrowing and deepening of the northern part of the basin between Oak Ridge and the southern margin of the Santa Ynez-Topatopa Mountains. In this part of the region there was nearly continuous deposition of marine clastic sediments from early Miocene to middle Pleistocene time. The northern mountains were being rapidly uplifted, folded, and eroded, and they furnished most of the debris and other materials that make up the Pliocene shale, sandstone, and soft conglomerate. A maximum of 14,000 feet of Pliocene, plus 3,500 to 5,000 feet of conformably overlying, mostly marine, lower Pleistocene sand, gravel, clay, and mudstone, filled the rapidly subsiding basin, which was 10 to 15 miles wide and 60 to 75 miles long. This is apparently the thickest Plio-Pleistocene section in the world, and this succession of 17,000 to 20,000 feet of strata, now dipping from 25° to vertical (even overturned in places) is well exposed north of Ventura and Santa Paula and vicinity. The lower part of the Pliocene section contains the largest accumulations of petroleum in the basin, mainly in the fields on the Ventura anticline, a few miles north of Ventura.

About mid-Pleistocene time the basin filling ceased and the main Coast Range orogeny occurred. During this surprisingly recent episode of strong mountain building, even the central part of the basin (except the western part beneath the Santa Barbara Channel, where movements may have been less intense) was raised to points more than 2,000 feet above the sea, and was complexly folded, faulted, and upthrust. Not until middle Pleistocene time could there have been a Ventura anticline, because the lower Pleistocene strata clearly are involved in the folding. This anticline, now steeply folded and severely faulted in the subsurface, is 16 miles long and contains nearly a billion barrels of oil and a great volume of natural gas. In middle Pleistocene time, the intra-basin anticlinal uplifts, such as South Mountain—Oak Ridge, with its several domal oil fields, and the marginal Santa Ynez—Topatopa Mountains and Santa Monica Mountains, were strongly rejuvenated and much more severely folded and faulted. Several steep to gently dipping thrusts developed as a result of the intense north-south compressive forces in the central part of the basin. Some, like the San Cayetano, Santa Susana, and Red Mountain thrusts, dip north, and others, like the Oak Ridge, Simi, and Santa Ynez reverse faults, dip south. These large faults have displacements of 5,000 to 15,000 feet or more. Numerous smaller faults and folds also were formed by these stresses.

In the northwest part of the basin, in southern Santa Barbara County, a series of intersecting, generally almost vertical faults with maximum displacements of about 5,000 feet are the principal structural features. Some of them trend northwest, and others trend northeast to east. These faults are of the oblique-slip type, having about as much horizontal as vertical movement. Several narrow anticlines and synclines developed before and during the faulting, and important quantities of petroleum have accumulated in the Elwood anticline and a few others.

Following the middle Pleistocene orogeny, a regional uplift of several hundred feet, accompanied by subdued folding and considerable faulting, has continued essentially to the present time, but probably at a slower pace. This is indicated by warped and faulted upper Pleistocene terraces. Small movements on some of the faults, such as the Mesa fault south of Santa Barbara (which apparently caused the destructive earthquake at Santa Barbara in June, 1925), are still continuing.

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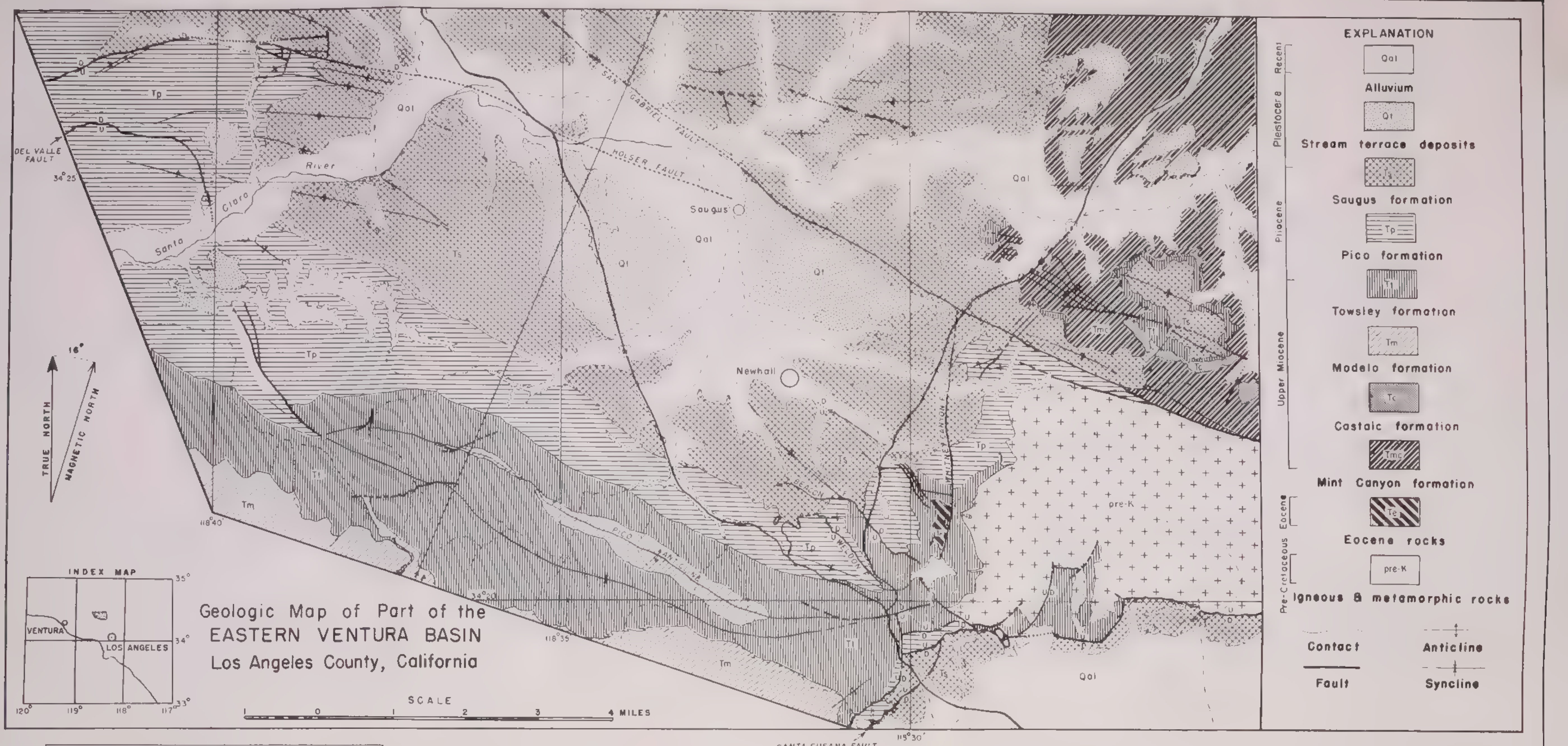
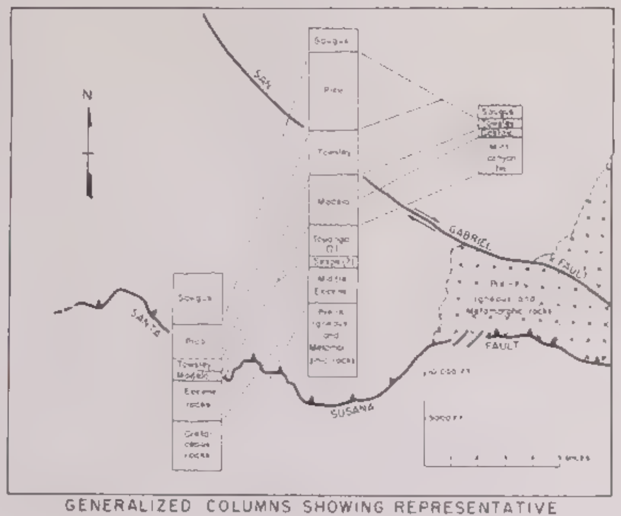
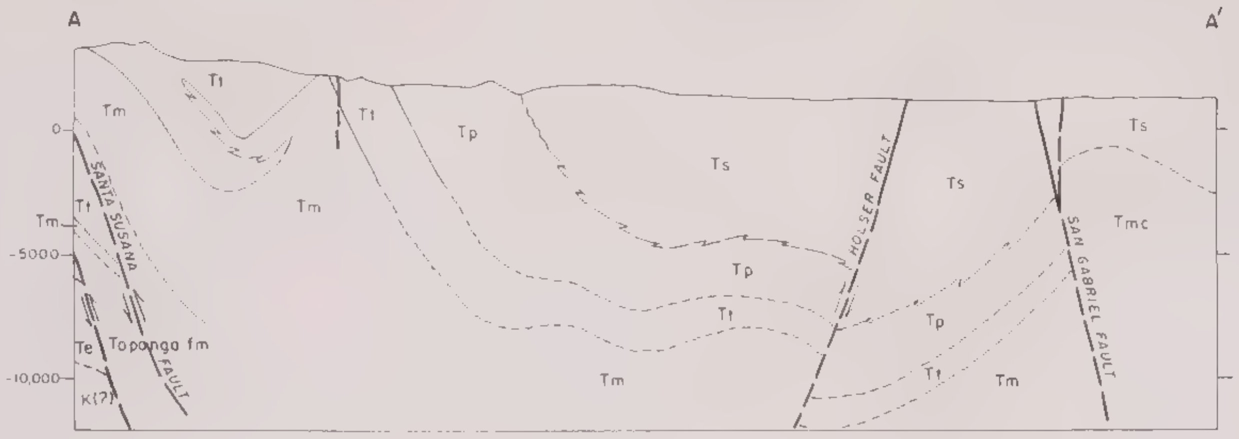
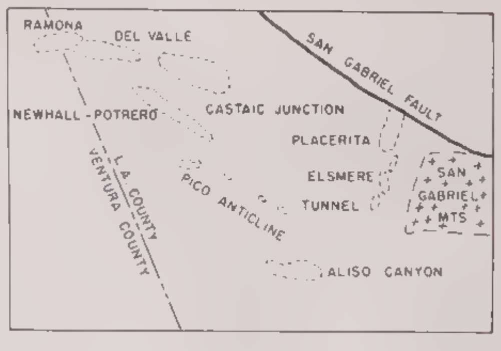
* Consulting Geologist, Ventura.


Geologic Map of Part of the
EASTERN VENTURA BASIN
Los Angeles County, California


GENERALIZED COLUMNS SHOWING REPRESENTATIVE SECTIONS IN EACH OF THREE PROVINCES


SECTION A—A'


Location of oil fields

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA
MAP SHEET No. 5

GEOLOGY OF A PART OF THE EASTERN VENTURA BASIN, LOS ANGELES COUNTY[*]

By Edward L. Winterer[†] and David L. Durham[†]

The eastern Ventura basin, a portion of which is shown on the accompanying geologic map, includes parts of three different depositional provinces, each having its own history of development. These provinces have been brought into juxtaposition as a result of major faulting. The depositional provinces, their bounding faults, and a generalized columnar section for each province are shown in one of the inset maps.

STRATIGRAPHY

Pre-Cretaceous Rocks. A complex of pre-Cretaceous igneous and metamorphic rocks makes up the core of the San Gabriel Mountains. A large body of anorthosite and norite is exposed north of the San Gabriel fault; south of the fault, schist, marble, and quartzite have been intruded by diorite gneiss and intermediate calc-alkaline plutonic rocks.

Cretaceous, Paleocene, and Eocene Rocks. South of the Santa Susana fault in the Simi Hills, a few miles southeast of the map area, about 5,000 feet of Upper Cretaceous marine strata is overlain by about 3,600 feet of Paleocene and about 1,800 feet of Eocene strata. Within the mapped area, in wells in the Aliso Canyon oil field (see inset map), Cretaceous and Eocene rocks are encountered beneath the Santa Susana fault.

In the mapped area the oldest sedimentary rocks north of the fault are middle or upper Eocene ("Domengine") marine sandstones that crop out in a small area 3 miles southeast of Newhall. A well 2 miles east of Newhall penetrated about 6,000 feet of Eocene strata before encountering crystalline rocks.

Sespe(?) Formation. Numerous wells in the vicinity of Newhall that reached Eocene rocks first penetrated a sequence of variegated sandstone, siltstone, and claystone as much as 1,800 feet thick beneath upper Miocene shale. These unfossiliferous continental deposits, which do not crop out, are probably equivalents of the Sespe formation, of late Eocene to early Miocene age.

Topanga(?) Formation. In the Aliso Canyon oil field a 2,500-foot sequence of lenticular sandstone and conglomerate, including a basalt flow, lies above the Santa Susana fault. No wells outside of that immediate area have encountered these rocks, which are correlated with the Topanga formation of middle Miocene age.

Modelo Formation. Unconformably overlying all these older sedimentary rocks is the marine Modelo formation of late middle Miocene and late Miocene age. The Modelo probably attains a thickness of at least 6,000 feet in the western part of the area but it thins toward the east, especially in the vicinity of Newhall, where it is overlapped by younger formations. South of the Santa Susana fault the Modelo is represented by less than 1,000 feet of sandstone and shale, which are overlapped southward by Pliocene strata. North of the fault the formation consists mainly of gray and brown clay shale and silty shale that are siliceous and diatomaceous in the lower part. Throughout the formation extensive lenses of thick-bedded sandstone, occasionally in units many hundreds of feet thick, are interbedded with the shale.

Mint Canyon Formation. The Mint Canyon formation, of late Miocene age, occurs only north of the San Gabriel fault. It consists of fluviatile sandstone and conglomerate and lacustrine mudstone that are equivalent in age to most of the Modelo formation. The Mint Canyon and Modelo formations do not interfinger; evidently they were deposited in separate basins and were brought into juxtaposition by large strike-slip movements along the San Gabriel fault.

Castaic Formation.[*] Unconformably overlying the Mint Canyon formation is the Castaic formation of late Miocene age, which consists in this area of a few hundred feet of marine sandstone. This formation also is present only north of the San Gabriel fault.

Towsley Formation.[*] The oldest rock unit recognizable both sides of the San Gabriel fault has been designated the Towsley formation (Winterer and Durham, 1951), of late Miocene and early Pliocene age.

The formation attains its maximum thickness along the north slope of the Santa Susana Mountains, where it overlies and interfingers with the Modelo formation and is a sequence of lenticular units of light-colored conglomerate and sandstone interbedded with units of brown-weathering mudstone. The formation is about 4,000 feet thick in the western part of the mapped area; eastward it thins to about 1,500 feet, and 3 miles southeast of Newhall it is overlapped completely by the younger Pico formation. Shallow-water, near-shore deposits of the formation are preserved east of Newhall, but elsewhere evidence from faunas and from sedimentary structures indicates deep-water deposition of the coarse-grained rocks by turbidity currents.

Pico Formation. The Pico formation of Pliocene age overlies the Towsley formation with a gradational contact throughout most of the area. East of Newhall the Pico overlaps the Towsley formation and rests on pre-Cretaceous crystalline rocks. In the western part of the area the Pico formation consists of about 5,000 feet of olive-gray and bluish-gray siltstone intercalated with lenses of sandstone and conglomerate. Foraminiferal faunas indicate that the lower part of the formation was deposited in relatively deep water and that the depth of water gradually decreased during the deposition of the remainder of the formation. The uppermost part of the Pico yields shallow-water faunas. As traced eastward and northward from the west-central part of the mapped area, the formation thins and the stratigraphic level of the first appearance of this shallow-water fauna occurs progressively lower in the section.

Immediately south of the Santa Susana fault, in the vicinity of the Aliso Canyon oil field, the Pico formation is about 6,000 feet thick. It thins markedly southward from the Aliso Canyon oil field.

Saugus Formation. The Pico formation is overlain by and interfingers with the Saugus formation of late Pliocene and early Pleistocene age. Locally an unconformity separates the two formations. The lower part of the Saugus formation consists of shallow-water marine, lagoonal, and brackish-water deposits of greenish siltstone and light-colored lenticular sandstone and conglomerate. These rocks grade upward into fluviatile mudstone, sandstone, and conglomerate. The Saugus may be as much as 6,000 feet thick along the south margin of the San Gabriel Mountains.

Terrace Deposits and Alluvium. Several levels of stream terrace deposits of probable late Pleistocene age blanket much of the area lying at low altitudes. Remnants of terrace deposits also occur at altitudes as much as 1,000 feet above the present Santa Clara River valley floor.

The main river valley and its tributaries are partly filled with alluvium, which is being removed in the present erosion cycle.

STRUCTURE

The Santa Susana and San Gabriel faults divide the eastern Ventura basin into three principal structural blocks. Appreciable differences between the stratigraphic columns in the three blocks indicate large-scale movements along these faults.

The San Gabriel fault, which dips steeply to the northeast in this area, brings together very dissimilar Miocene stratigraphic sequences, but the post-Miocene sequences are not markedly unlike on opposite sides of the fault; in fact, the surface trace of the fault where it traverses the Saugus formation is obscure for several miles along its trend northwest of the town of Saugus and is marked only by a zone of small faults and steep dips. These facts suggest that movement along the fault began at least as early as the end of the Miocene epoch. Evidence for right-lateral offset of coarse conglomerate and breccia of late Miocene age from their source areas, indicating post-Miocene strike-slip movement of at least 15 miles along the San Gabriel fault, has been presented by Crowell (1952).

The principal deformation in the Ventura basin occurred during the Pleistocene epoch, after deposition of the Saugus formation. The thick prism of weak rocks north of the Santa Susana fault was compressed into a series of west-northwest-trending folds broken by south-dipping reverse faults. Along the north-dipping Santa Susana fault, this thick section of rocks has been thrust southward over a much thinner section of Miocene and Pliocene rocks that overlie resistant Cretaceous rocks. In the eastern part of the area the Santa Susana fault continues as a zone of faults (the Sierra Madre fault system) along which the pre-Cretaceous crystalline rocks of the San Gabriel Mountains have been thrust southward over Tertiary rocks.

ECONOMIC GEOLOGY

Petroleum. Production of petroleum from the area began about 1850, when oil was collected from seeps near the axis of the Pico anticline, but commercial operations did not begin until 1875. Early exploration was mainly near these seeps and also in the region east of Newhall, where tar sands of Pliocene age associated with seeps unconformably overlie Eocene rocks that contain small amounts of high-gravity oil. Search for oil is still active in the latter area, and most of the production comes from lower Pliocene rocks in small fault traps.

Most of the oil from the mapped area is recovered from lenticular upper Miocene rocks in four anticlinal fields: Newhall-Potrero, Castaic Junction, Del Valle, and Ramona (see inset map).

In the Aliso Canyon field oil is produced from Pliocene (Pico), middle Miocene (Modelo), and Eocene rocks in a complicated fault trap between breaks overridden and concealed by the Santa Susana fault.

Gold. Of historical interest is the fact that some of the first gold produced in California was from stream gravels in the western San Gabriel Mountains, which were worked by Mission fathers as early as 1834.

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[*] Publication authorized by the Director, U. S. Geological Survey.

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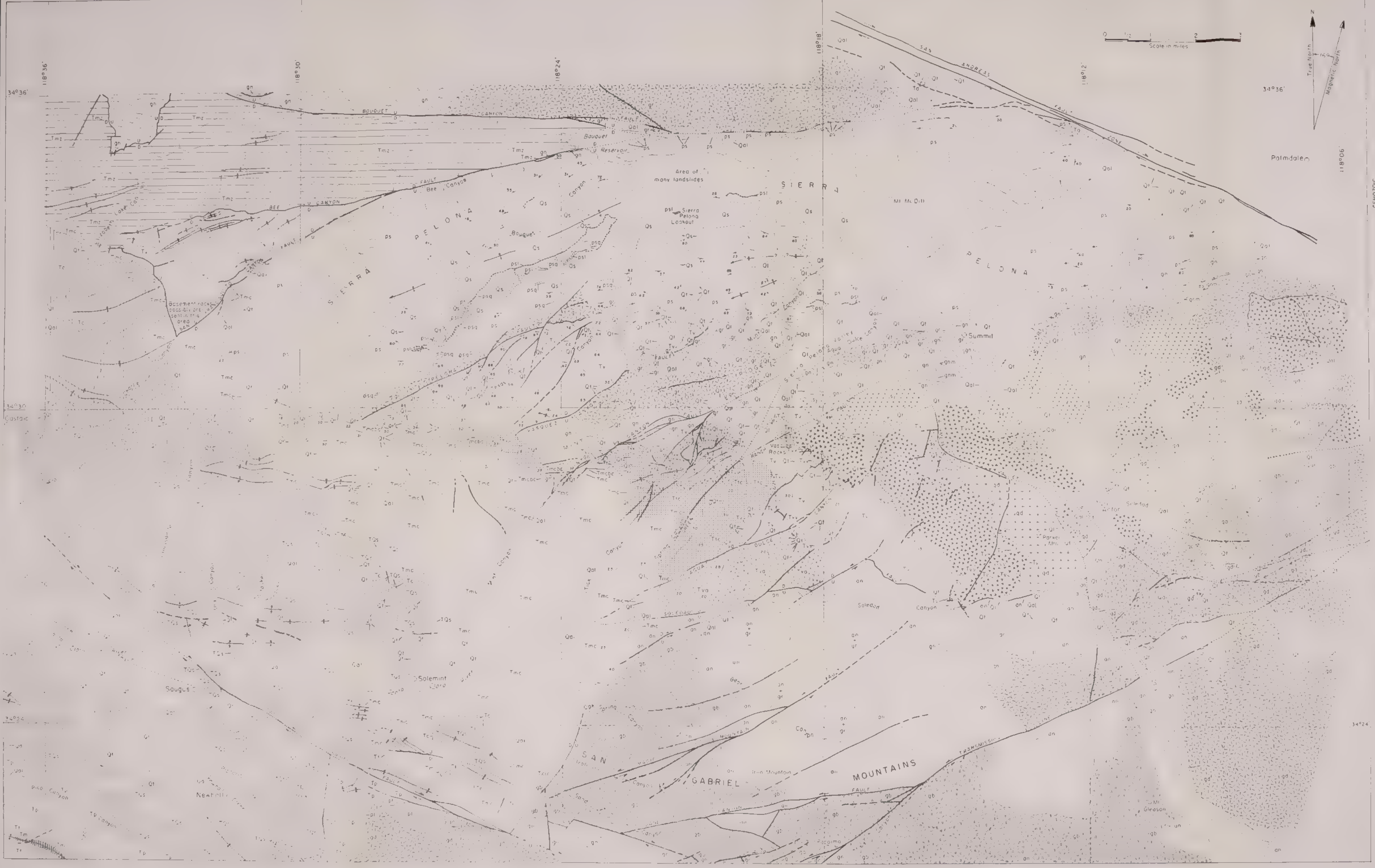
DIVISION OF MINES
OLAF P. JENKINS, CHIEF

STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 170 M S 6



EXPLANATION

SEDIMENTARY ROCKS

CENOZOIC
QUATERNARY
TERTIARY
Recent
Pleistocene
Pliocene
Miocene
Paleocene Oligocene (?)

Qal
Alluvium

Qs
Landslide deposits

Qt
Terrace deposits

TQs
Saugus formation

Tt
Towsley formation

Tc
Castaic formation

Tmc
Tmcbc
Mint Canyon formation, with schist-bearing basal conglomerate (Tmcbc)

Ttc
Tick Canyon formation

Tva
Tv
Vasquez formation, with anorthosite-rich cobble conglomerate (Tva) at top

Tmz
Martinez formation

Sedimentary formations that appear outside the Soledad basin

Ta
Anaverde formation (nonmarine arkose, conglomerate and siltstone)

Tp
Pico formation (marine sandstone and siltstone)

Tm
Modelo formation (marine sandstone, siltstone, and conglomerate)

IGNEOUS AND METAMORPHIC ROCKS

CENOZOIC
Miocene or Oligocene (?)

Tvv
Volcanic rocks associated with Vasquez formation

MESOZOIC
JURASSIC and/or CRETACEOUS
PALEOZOIC (?)
PRE-CAMBRIAN (?)

gr
Granite and other quartz-bearing plutonic rocks, undivided

gd
Granodiorite

sy
Quartz-bearing syenite

qd
Quartz diorite

di
Diorite

gnm
Mafic gneiss

gn
Gneiss complex

pl
Placerita formation

gb
Mafic gabbroic rocks

an
Anorthosite

psl
psq
ps
Pelona schist, with quartzite (psq) and interbedded limestone and quartzite (psl)

Plutonic rocks with many inclusions of older rocks and local masses of hybrid rocks

Anorthosite complex

NOTES

All sedimentary formations in main column are separated by unconformities.

Individual units in the section of pre-Tertiary igneous and metamorphic rocks are not necessarily shown in order of their respective ages.

SYMBOLS

Geologic contact, dashed where approximately located and queried where inferred

U
D
Fault, showing sense of major movements, dashed where approximately located and dotted where buried

Axes of syncline and anticline, showing direction of plunge, dashed where approximately located and dotted where buried

Geology compiled by W. R. Muehlberger, 1953, and R. H. Johns, 1954

Based on mapping by

P. C. Bateman
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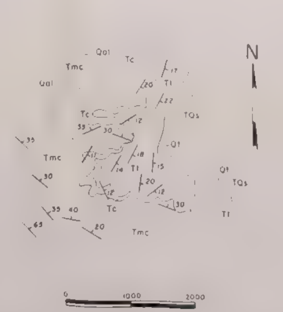
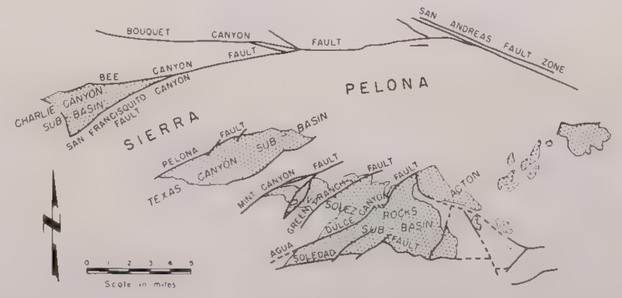


Map showing relations of Mint Canyon, Castaic, Towsley, and Saugus formations on hill about one mile south-southeast of Solemint



Map showing distribution of major faults, present outcrop areas of the Vasquez formation and associated volcanic rocks, and general positions of sub-basins of Vasquez deposition

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BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 6

GEOLOGY OF THE SOLEDAD BASIN, LOS ANGELES COUNTY †

By Richard H. Jahns * and William R. Muehlberger **

GENERAL FEATURES

The Soledad basin lies immediately north of the western San Gabriel Mountains, in the Transverse Range province of southern California, and its center is about 35 miles north of the Los Angeles civic center. It is about 30 miles long, as measured in an east-west direction, and is 8 to 12 miles wide. The floor of the basin is highly irregular, and ranges in general relief from about 400 feet in its western part to as much as 2,500 feet near its eastern end. Drainage is mainly southwest and north from the areas on opposite sides of Soledad Canyon, which trends westward and broadens into the eastern end of the Santa Clara River Valley.

The basin is bounded on the north, east, and south by ridges and mountain masses of relatively old crystalline rocks. These, together with ancestral highland masses that appear to have had essentially the same general distribution, contributed large quantities of sediments to the basin during much of Cenozoic time. More than 20,000 feet of stratified rocks was laid down under dominantly nonmarine conditions in the elongate lowland area, and an additional 4,500 feet of andesitic and basaltic volcanic rocks accumulated locally. Thick sections of marine strata may also have been deposited in the basin during at least two episodes of broad submergence, but nearly all of these rocks were subsequently removed by erosion.

Essentially an open syncline with locally wrinkled flanks and a prevailingly westward plunge, the Soledad basin appears to have been defined as a trough of deposition mainly by faults, and to have received much of its sedimentary fill in a manner that was very irregular in detail. Repeated diastrophism both within and along the margins of the basin is attested by numerous faults, folds, and unconformities, as well as by the distribution and lithology of the sedimentary rocks.

Near the east end of the present topographic basin, strata of early Tertiary age rest with depositional contact upon much older crystalline rocks, and a short distance farther east this basement terrane is sharply separated from rocks of the western Mojave Desert region by the San Andreas fault. Along its present southern margin, the basin is bounded from the San Gabriel Mountains by the Soledad fault, and along a part of the northern margin the Pelona fault bounds it from the high ridge of the Sierra Pelona.

To the west the Soledad basin terminates against the San Gabriel fault, beyond which lies the eastern part of the much larger Ventura basin. No major topographic break marks this boundary, and, indeed, the Soledad basin has often been referred to as the easternmost Ventura basin. Although both basins do contain thick sections of Cenozoic strata, the history and conditions of sedimentation appear to have been so different on opposite sides of the San Gabriel fault that they are best regarded as separate units.

Some of the strata of the Soledad basin are traceable northwestward into the Ridge basin, a narrow, northwest-trending trough that also lies on the east side of the San Gabriel fault. It contains an enormously thick section of upper Tertiary rocks (Crowell, Map Sheet No. 7, this volume), and its history evidently was quite different from the histories of the nearby Ventura and Soledad basins.

The rocks exposed in and adjacent to the Soledad basin range in age from pre-Cambrian to Recent, and embrace numerous metamorphic, plutonic, volcanic, and sedimentary types. These are discussed below in approximate order of decreasing age, and mainly from the standpoint of their distribution, structure, and bearing on the history of the basin. Data on thickness and lithology of the major rock units appear in the accompanying stratigraphic column.

PRE-CENOZOIC ROCKS

Pelona Schist. The Pelona schist, which forms the large Sierra Pelona ridge, is a thick sequence of mildly metamorphosed, fine-grained, foliated rocks that originally were graywacke, subordinate volcanic rocks of basic composition, and minor amounts of orthoquartzite and limestone. This formation appears to antedate all the other rocks in the area, and may well be pre-Cambrian in age, as suggested by Simpson (1934, pp. 380-381).

Anorthosite Complex. Anorthosite and related norite, gabbro, mafic diorite, and numerous dike rocks are widely exposed in the western San Gabriel Mountains, and also appear as small masses near the eastern end of the Soledad basin. Many of these rocks are distinguished by extreme coarseness of grain, by giant poikilitic textures, by pervasive shearing and shattering on a wide variety of scales, by distinctive mineralogy (e.g., andesine anorthosite, ilmenite-magnetite rocks), or by some combination of these features. They are abundantly represented among the clasts in the Cenozoic strata of the nearby basin. The anorthosite complex is plainly older than the plutonic rocks of less basic composition that are in contact with it, and recent geochemical work by Neuerburg and Gottfried (1954) has demonstrated a pre-Cambrian age for two members of the complex.

Placerita Formation and Feldspathic Gneisses. The Placerita formation, comprising schist, quartzite, marble, and other foliated rocks of sedimentary origin, forms inclusions and septa in the younger plutonic masses of the western San Gabriel Mountains. It may be of pre-Cambrian age and older than the Pelona schist, as suggested by Miller (1934, pp. 3-12, 63-65), or it may be correlative with masses of Paleozoic strata that are present farther east in the range.

Feldspathic gneisses of several types are widespread in the San Gabriel Mountains, where they have been termed the San Gabriel formation by Miller (1934, pp. 12, 25-65), and they also appear in a well-defined belt that extends from the southeastern margin of the Sierra Pelona westward and west-southwestward to the Mint Canyon Ridge, within the Soledad basin. Included among these rocks are granitic to granodioritic augen gneisses, gneissic intrusive rocks of granitic to dioritic composition, amphibole-rich gneiss, and local interlayered schist, quartzite, amphibolite, and limestone. A large part of the gneissic terrane is clearly of hybrid origin, and some of the gneisses may be parts of the Placerita formation that have been intimately injected by younger igneous material.

Mesozoic Intrusive Rocks. Plutonic rocks that range in composition from diorite to granite form large parts of the San Gabriel Mountains, and also are widely exposed at the eastern end of the Soledad basin and on the Mint Canyon Ridge. These rocks are similar to the Mesozoic intrusives in many other parts of southern California, and at least some of those in the San Gabriel Mountains have been found, through geochemical determinations, to be late Mesozoic in age (G. J. Neuerburg, personal communication). Much of the material in the sedimentary section of the Soledad basin has been derived from these plutonic rocks, and clasts of certain distinctive rock types have formed a basis for tentative correlations between the containing strata and probable source areas.

THE CENOZOIC SECTION

Martinez Formation. Fossiliferous marine clastic strata that have been referred to the Paleocene Martinez formation occupy a large, elongate, down-dropped fault block on the northwest side of the Sierra Pelona. This section is at least 6,000 feet thick in the map area, and thickens northwestward to about 12,500 feet near the margin of the Ridge basin. The same formation is preserved in areas that lie west, south, and east-southeast of the Soledad basin, and it seems likely that it once covered an enormous area, including at least a part of what is now the San Gabriel Mountains. This widespread Paleocene sea probably extended eastward well into the Mojave Desert region.

Vasquez Formation. Following uplift and wholesale erosion of the Martinez beds, the Soledad basin was first defined in late Eocene or early Oligocene time, and subsequently received as much as 12,500 feet of fluviatile and locally lacustrine sediments that constitute the Vasquez formation. Conglomerates and breccias form a large part of the sequence, which consists chiefly of material derived from nearby source areas. Deposition of all but the uppermost part of the section appears to have been confined to three separate troughs, or sub-basins, that were at least partly defined by major faults. The positions of these sub-basins are marked in a general way by the present outcrop areas of Vasquez strata (see inset map). Additional areas of deposition farther east, beyond the map area, are indicated by remnants of Vasquez sediments along the north base of the San Gabriel Mountains.

The uppermost part of the formation appears to have once extended across the entire Soledad basin, evidently as a broad alluvial apron that was built northward from the San Gabriel Mountains after the deeper sub-basins had been filled with sediment of more local derivation. The preserved remnants of this apron are very coarse grained, and in most places are composed almost wholly of fragments of anorthosite and related gabbroic rocks.

The Vasquez formation contains numerous beds and lenses of megabreccia, many of which are monolithologic and some of which are truly cyclopean. They range in thickness from a few inches to many tens of feet, and most of their contained fragments range in diameter from less than an inch to 30 feet. Larger fragments are not rare. Nearly all of these breccias are plainly parts of the sedimentary section, and appear to have been deposited as mud flows and debris flows.

Interlayered with the sedimentary strata, chiefly in the lower part of the section and in the eastern half of the basin, are flows, breccia masses, and intrusive sheets of andesite and basalt. In upper Tick Canyon they are associated with fine-grained lacustrine strata that contain borate minerals. These volcanic rocks also extend eastward beyond the outcrop areas of the sediments, where they rest directly upon older crystalline rocks and in part have been faulted down against them

No diagnostic fossils have been obtained from the Vasquez formation, but it probably corresponds to at least a part of the Sespe formation in the Ventura basin to the west. Vertebrate fossils indicate a late Eocene to early Miocene age range for the Sespe, and the Vasquez is provisionally assigned to the Oligocene epoch.

Tick Canyon Formation. Overlying the Vasquez formation and older rocks with a pronounced unconformity is the terrestrial Tick Canyon formation, which has been dated as lower Miocene or lowermost middle Miocene on the basis of vertebrate fossils (Jahns, 1940). The unconformity is the most important one in the Soledad basin, and it marks a period of vigorous faulting, local tight folding, and widespread erosion that removed a substantial part of the Vasquez section. During a part of the time represented by this stratigraphic break, the basin may have been occupied by marine waters.

Most of the Tick Canyon sediments appear to have accumulated in two shallow sub-basins that were separated by the Mint Canyon Ridge. Unlike the Vasquez strata, they contain abundant clasts of volcanic rocks, including rhyolite and darker-colored types whose nearest known outcrop areas are in the Mojave Desert region to the northeast.

Mint Canyon Formation. The Mint Canyon formation, of late Miocene age, unconformably overlies the Tick Canyon formation and a faulted mosaic of all the older formations, and was deposited over a broad area. It is mainly medium- to coarse-grained and fluviatile, and also contains fine-grained beds that were laid down in at least two large and shallow fresh-water lakes. Several beds of light-colored tuff attest to sporadic volcanic activity in the area.

Vertebrate fossils obtained from the Mint Canyon section, and especially from its upper half, have been interpreted in different ways by different paleontologists, and the major elements of disagreement are summarized elsewhere in this volume (Durham, et al., Contribution 7, Chapter III). It seems clear, however, that the Mint Canyon formation is equivalent in age to much of the marine upper Miocene Modelo formation of the Ventura basin. The two formations do not interfinger, as pointed out by Winterer and Durham (Map Sheet No. 5), mainly because they were deposited in separate basins and subsequently were juxtaposed by large strike-slip movements on the San Gabriel fault (Crowell, 1952).

Castaic Formation. The highly fossiliferous marine Castaic formation, of late Miocene age, overlies the Mint Canyon section with a distinct angular unconformity (see inset map). From an average of about 600 feet in the Soledad basin, it thickens progressively northwestward to at least 7,000 feet in the Ridge basin. It has been included with the Modelo formation by some investigators, and has been referred to informally as "Modelo" by others, but it differs lithologically from the typical Modelo section and was deposited in a separate basin.

Towsley Formation. The marine Towsley formation, which lies unconformably upon the Castaic and Mint Canyon formations north of the San Gabriel fault (see inset map), is the oldest stratigraphic unit that can be recognized on both sides of the fault (Winterer and Durham, Map Sheet No. 5). In the Soledad basin it consists of fossiliferous, dominantly fine-grained, shallow-water sediments, but elsewhere it is coarser grained and was deposited in deep water.

Saugus Formation. The Plio-Pleistocene Saugus formation lies unconformably upon the Towsley, Castaic, and Mint Canyon formations. It is mainly fluviatile in the areas north of the San Gabriel fault, but fine-grained marine and brackish-water deposits appear locally in its basal part. It thickens considerably toward the west and south.

Post-Saugus Deposits. Several hundred feet of poorly consolidated sands and gravels appear as remnants of a once-extensive fluviatile deposit that filled the upper Santa Clara River Valley in Pleistocene time, after it had been cut down through a considerable thickness of Saugus and older strata. Still younger terrace deposits appear at several lower levels in the valley, and represent episodes of renewed downcutting.

Terrace deposits of probable late Pleistocene age mantle extensive surfaces that were best developed in areas underlain by the Saugus and Mint Canyon formations on both sides of the valley, and similar deposits are preserved at higher levels to the north and east. Especially prominent are those in the upper parts of Mint, Agua Dulce, and Escondido Canyons. Many of these deposits contain abundant clasts of volcanic rocks whose sources probably lay in the Mojave Desert region to the northeast.

Large landslide masses, of probable late Pleistocene and Recent age, are common on the flanks of the Sierra Pelona and also appear locally in the western part of the basin south of Solemint. The Santa Clara River Valley, Soledad Canyon, and their major tributaries are floored with Recent alluvium, much of which is being dissected at the present time.

STRUCTURE

Faults. The Soledad basin and Sierra Pelona constitute a large and elongate structural block that has the general outline of a flattened parallelogram. This block is bounded on the north by the Clearwater-Bouquet Canyon zone of reverse faulting, on the south by the Soledad normal fault, and on the northeast and southwest by the right-lateral San Andreas and San Gabriel faults, respectively. So large have been the movements along these faults that most of the Tertiary rocks within the block cannot be correlated with the rocks that border the block.

Prominent within the Soledad basin are northeast-trending left-lateral faults, some of which offset older normal faults that trend more nearly east. The major movements along most of these faults antedated deposition of the Tick Canyon and Mint Canyon formations, and may well have been recurrent during the period between upper Eocene and lower Miocene time. Later movements along several of the faults have offset the younger formations.

The east-trending Soledad fault, one of the few major normal faults in the region, is an old break that probably has not been active since the beginning of Tick Canyon time. It is cut off by the San Andreas fault to the east, beyond the map area, and is offset in a left-lateral sense by several northeast-trending faults in the Soledad basin. It almost certainly extends westward beneath the Santa Clara River Valley, where it is buried under the Mint Canyon and Tick Canyon formations; these formations rest upon a thick section of Vasquez strata north of the valley, whereas the Mint Canyon formation rests directly upon older crystalline rocks south of the valley.

Folds. The Sierra Pelona is essentially an old, broad anticline in the Pelona schist. This fold plunges gently west-southwest. The Martinez and Sespe strata that occupy the fault-bounded wedge immediately north of the western Sierra Pelona have been much more tightly compressed into numerous folds, several of which are overturned toward the south.

The broad syncline of the Soledad basin is marked locally by smaller folds. The Vasquez section in the upper Tick Canyon area has been compressed into tight folds with west to southwest trend, and has been ruptured in a complex way by faulting. Much of this deformation antedated deposition of the Tick Canyon formation. The younger strata also have been compressed, in most places rather gently, into broad folds whose axes trend northwest to west. Even the Saugus formation has been deformed, especially in areas adjacent to the San Gabriel fault. Episodes of tilting are reflected by the angular unconformities that appear in several parts of the Cenozoic section.

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GENERALIZED STRATIGRAPHIC COLUMN FOR THE SOLEDAD BASIN

AGE			MAP SYMBOL	ROCK UNIT		THICKNESS (FEET)	LITHOLOGY
CENOZOIC	QUATERNARY	PLIOCENE PLEISTOCENE RECENT	Qal	Alluvium and talus deposits		0-75	Unconsolidated silt, sand, and gravel
			Qs	Landslide deposits		0-150	Contorted silty deposits and pebbly to bouldery rubble.
			Qt	Terrace deposits and older valley fill		0-60 0-450	Unconsolidated to partly consolidated gray to reddish brown sand, gravel, and silt.
			TQs	Saugus formation		0-1,200	Poorly consolidated gray to light pinkish brown conglomerate, sandstone, and siltstone, mainly nonmarine.
	TERTIARY		Tt	Towsley formation		0-250	Gray to brown siltstone with subordinate gray sandstone and pebble conglomerate, marine.
		MIOCENE	Tc	Castaic formation		0-800	Gray, bluff, and brown siltstone, sandstone, and subordinate conglomerate, with lenses of cobble conglomerate and local oyster and pecten reefs in basal part; marine.
			Tmc	Mint Canyon formation	Upper member	0-2,600	Light gray and locally greenish gray sandstone and conglomerate, with thick lenses of lacustrine siltstone and several beds of white tuff, nonmarine
					Lower member	0-1,900	Variegated sandstone, siltstone, and conglomerate, more conglomeratic and prevailingly reddish brown in lower part, rubbly schist-bearing conglomerate (Tmcbc) at base west of Mint Canyon; nonmarine.
			Ttc	Tick Canyon formation		0-900	Buff to reddish brown, locally variegated siltstone, sandstone, and conglomerate, with coarse basal conglomerate of granitic debris west of Mint Canyon and volcanic debris east of Mint Canyon; nonmarine
		OLIGOCENE?	Tv	Vasquez formation with associated andesite and basalt		0-12,500	Light gray to dark reddish brown arkose, sandstone, and conglomerate, with numerous lenses of megabreccia and local finer-grained facies that contains calcareous beds and borate minerals, anorthosite-rich cobble conglomerate, Tva, near mouth of Agua Dulce Canyon; nonmarine.
			Tvv			0-4,200	Gray, brown- and greenish-brown—weathering andesite and basalt sills, flows, and breccia masses; some flows very amygdaloidal
		PALEOCENE	Tmz	Martinez formation		6,000 ±	Gray, buff, and brown sandstone, siltstone, and subordinate conglomerate, very well indurated; marine.
MESOZOIC	JURASSIC AND/OR CRETACEOUS		gr qd gd sy di	Plutonic igneous rocks			Granodiorite, quartz diorite, quartz monzonite, quartz syenite, granite, and diorite, with dike rocks and local inclusions and septa of schist and gneiss, numerous masses of hybrid rocks also are present
PRE-CAMBRIAN OR PALEOZOIC			gn gnm	Gneiss complex			Biotite schist, amphibolite, and granitic to dioritic gneiss, commonly mixed with younger igneous material
			pl	Placerita formation		800-2,500 +	Schist, gneiss, quartzite, and marble, in part injected by younger igneous rocks.
PRE-CAMBRIAN?			an gb	Anorthosite complex			Anorthosite and related gabbroic rocks.
			ps psl psq	Pelona schist		7,500 +	Muscovite schist, biotite schist, chlorite schist, and actinolite-chlorite schist, with subordinate interbedded marble and quartzite.

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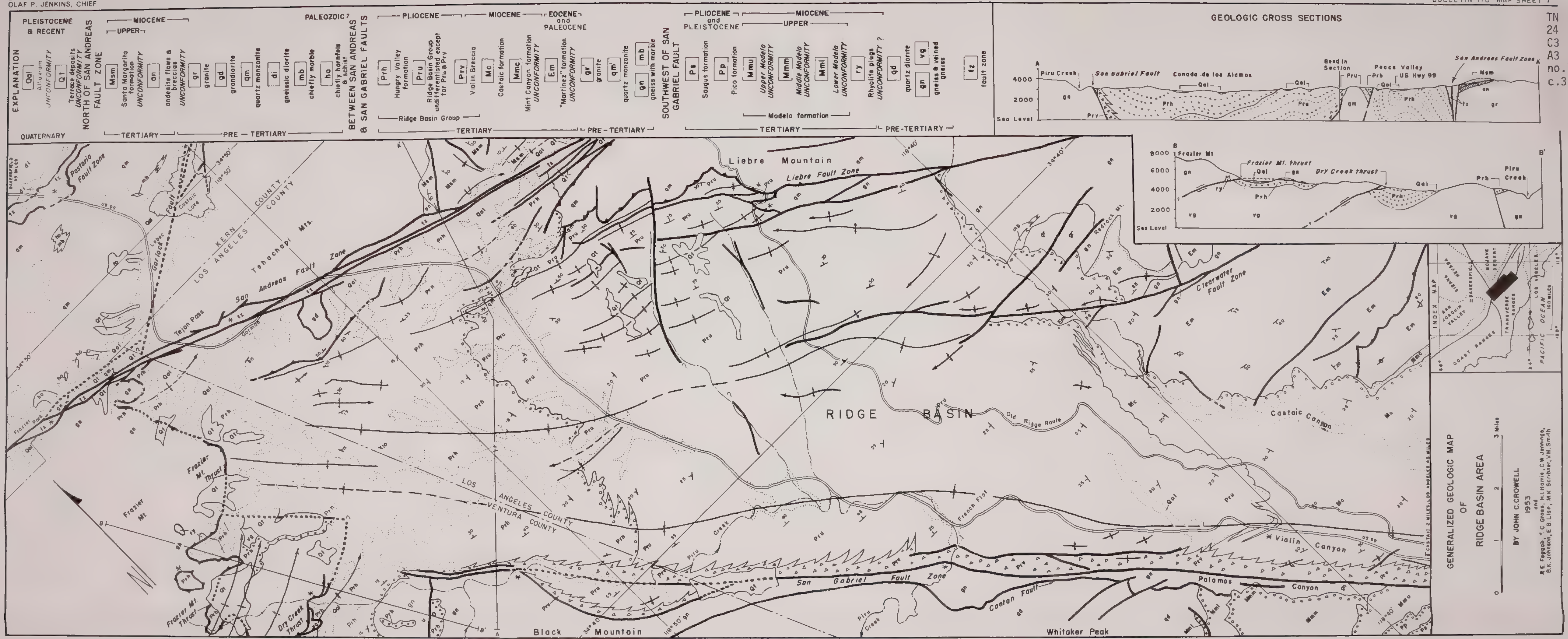
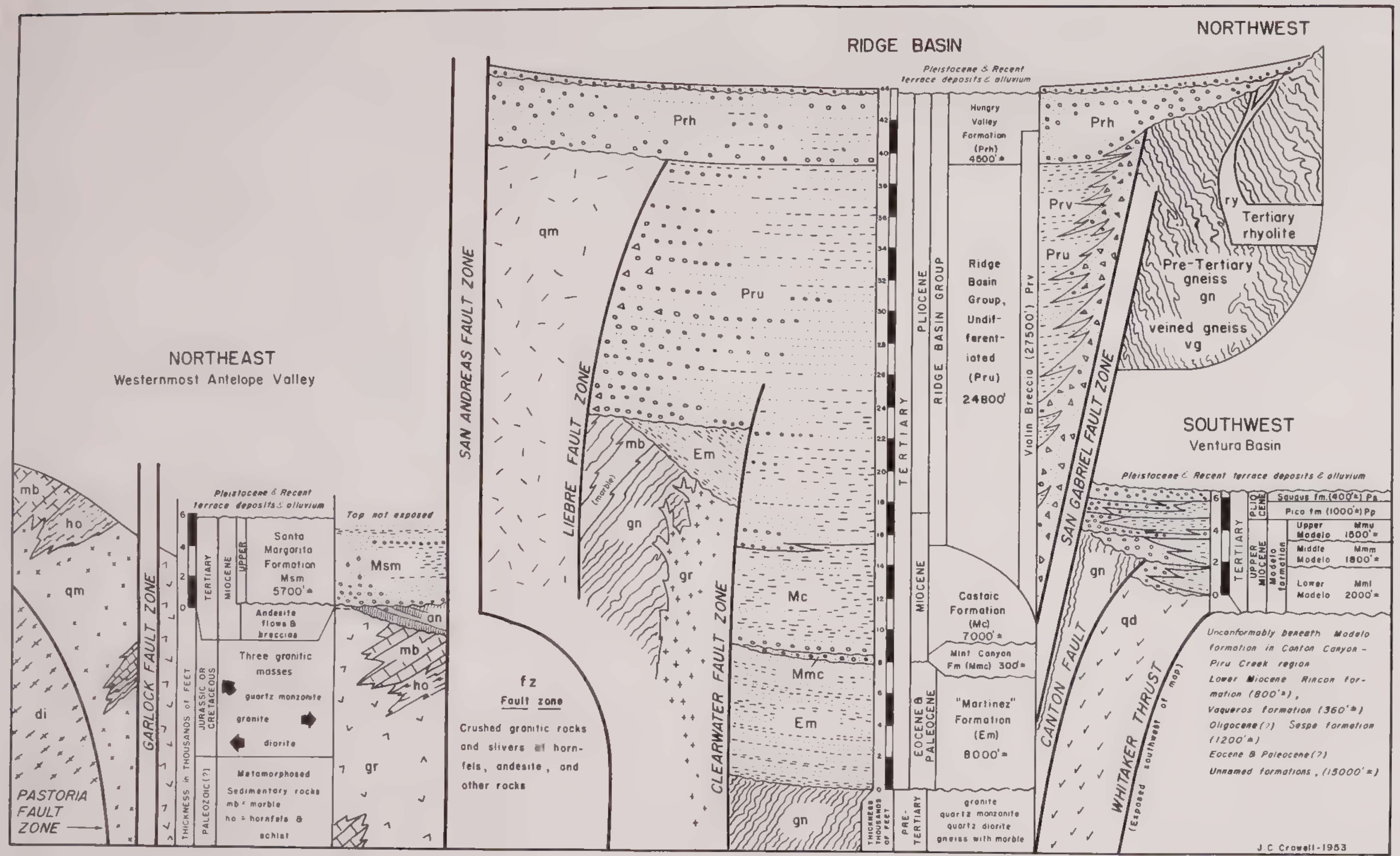


GENERALIZED GEOLOGIC MAP OF RIDGE BASIN AREA

0 1 2 3 Miles

BY JOHN C. CROWELL
1953
and
R.E. Foggoli, T.C. Gross, H.I. Harris, C.W. Jennings,
B.K. Johnson, E.B. Lian, M.K. Scribner, V.M. Smith


NORTHEAST
Westernmost Antelope Valley
RIDGE BASIN
NORTHWEST
SOUTHWEST
Ventura Basin
PASTORIA FAULT ZONE
GARLOCK FAULT ZONE
SAN ANDREAS FAULT ZONE
LIEBRE FAULT ZONE
CLEARWATER FAULT ZONE
SAN GABRIEL FAULT ZONE
CANTON FAULT
WHITAKER THRUST (Exposed southwest of map)
Pleistocene & Recent terrace deposits & alluvium
Top not exposed
Santa Margarita Formation Msm 5700'±
Andesite flows & breccias
Three granitic masses
quartz monzonite
granite
diorite
Metamorphosed Sedimentary rocks mb = marble ho = hornfels & schist
TERTIARY
MIOCENE
UPPER
JURASSIC OR CRETACEOUS
PALEOZOIC(?)
THICKNESS in THOUSANDS of FEET
mb
ho
qm
di
gr
an
Msm
fz
Fault zone
Crushed granitic rocks and slivers of hornfels, andesite, and other rocks
Prh
Pru
Prv
Mc
Mmc
Em
gn
Hungry Valley Formation (Prh) 4800'±
Ridge Basin Group, Undifferentiated (Pru) 24800'
Violin Breccia (27500') Prv
Castaic Formation (Mc) 7000'±
Mint Canyon Fm (Mmc) 300'±
"Martinez" Formation (Em) 8000'±
granite quartz monzonite quartz diorite gneiss with marble
PLIOCENE
RIDGE BASIN GROUP
EOCENE & PALEOCENE
PRE-TERTIARY
THICKNESS THOUSANDS OF FEET
ry
Tertiary rhyolite
Pre-Tertiary gneiss gn
veined gneiss vg
qd
Saugus fm (400'±) Ps
Pico fm (1000'±) Pp
PLIOCENE
UPPER MIOCENE
Modelo formation
Upper Modelo Mmu 1800'±
Middle Modelo Mmm 1800'±
Lower Modelo Mml 2000'±
Unconformably beneath Modelo formation in Canton Canyon - Piru Creek region
Lower Miocene Rincon formation (800'±),
Vaqueros formation (360'±)
Oligocene(?) Sespe formation (1200'±)
Eocene & Paleocene(?)
Unnamed formations, (15000'±)
J.C Crowell-1953

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 7

GEOLOGY OF THE RIDGE BASIN AREA, LOS ANGELES AND VENTURA COUNTIES

By John C. Crowell[*]

The Ridge Basin area provides a three-dimensional view of an old intermontane basin or bolson that was filled with a great thickness of clastic sediments during its formation and then was deformed, uplifted, and laid bare by erosion. During late Tertiary time the basin was a narrow depression, bounded on the southwest by the scarp of the San Gabriel Fault zone and on the northeast by highlands that had been raised chiefly by movement on the Clearwater, Liebre, and other faults. Large amounts of sediment were washed in from these highlands as the bolson was formed, and deposition and deformation went on hand in hand. Owing to later (Quaternary) folding and uplift, followed by erosion, the sedimentary section is now clearly exposed. The sediments grade sharply from conglomerate and sandstone on the northeast to predominantly shale along the axis of the trough, and thence southwestward to coarse sedimentary breccia against the San Gabriel fault zone. Some of California's largest faults are well exposed around the margins of the basin; these deform the older rocks more severely than the younger ones, and commonly are marked by conspicuous zones of rock-slivers, thoroughly fractured rock, and gouge.

Thousands of people every day travel U. S. Highway 99 between Castaic and Gorman, through the axial part of the Ridge Basin, and view 33,000 feet of strata that dip gently to moderately northwest. This is one of the thickest known sections of upper Miocene and Pliocene rocks. A round trip along this highway and the Old Ridge Route to the northeast, with a few side trips, will provide access to the major features of the area. Points of special interest are marked on the accompanying map by asterisks, and the general stratigraphic and structural relations are shown diagrammatically in the adjacent sketch.

The oldest rocks of the area consist of gneisses, migmatites, and deeply eroded granitic rocks south of the San Andreas fault. North of this fault the rocks are granitic types with roof pendants and stope blocks of marble, schist, and hornfels that represent an original sedimentary section of probable Paleozoic age. The basement rocks generally differ markedly on opposite sides of the great faults in the region, and many exposures are characterized by severe crushing and fracturing. Plugs of Tertiary rhyolite and obsidian are intrusive into gneiss on the south flank of Frazier Mountain, and flows of Miocene (?) andesite lie beneath Santa Margarita (upper Miocene) sandstone, shale, and conglomerate at the western end of Antelope Valley.

The oldest unmetamorphosed sedimentary rocks are Paleocene and Eocene sandstone, shale, and subordinate conglomerate that have been referred to the Martinez formation. These rocks, which reach a thickness of about 12,000 feet just east of the map area, are lithologically similar to strata of approximately the same age southwest of the San Gabriel fault at the northern edge of the Ventura basin. Unlike the younger parts of the section, the Martinez formation was at one time rather widespread in the region, and was not laid down concurrently with movement on the San Gabriel fault.

Upper Miocene and Pliocene sedimentary rocks, which unconformably overlie both the Martinez formation and basement rocks, were deposited mainly during periods of deformation in the region, and subsequently have been squeezed and folded between the competent walls of Ridge Basin. They now plunge gently toward the northwest. On the southeast, where the rocks of the Ridge Basin grade into those of the eastern Ventura basin, the stratigraphic section has been divided into: (1) the Mint Canyon formation (middle and upper Miocene), which occurs in the map area as a thin tongue of reddish conglomerate; (2) the Castaic formation (upper Miocene); and (3) the Ridge Basin group (upper Miocene and Pliocene). The Castaic formation, as exposed in the type locality along the lower reaches of Castaic Canyon north of Castaic, consists of at least 7,000 feet of shale with interbedded sandstone and minor beds of pebble conglomerate. It overlies unconformably the Mint Canyon formation and crops out only northeast of the San Gabriel fault. Previous investigators have included it in the Modelo formation, but it differs lithologically from the Modelo of the Ventura basin and thus can be differentiated.

The Ridge Basin group, about 29,000 feet thick, lies conformably above the Castaic formation with an interfingering contact that is marked by an abrupt upward increase in the proportion of sandstone beds. The lowermost 2,000 feet of the group is marine and contains upper Miocene mollusks and *Foraminifera*, but the bulk of the section is nonmarine. The determination of its age, late Miocene and Pliocene, rests upon its stratigraphic position, vertebrate remains obtained from the upper part of the section (Stock, in Crowell, 1950, p. 1638), and plant and fish remains obtained from the middle part of the section (Axelrod, 1950; David, 1945).

On the map only two formations of the Ridge Basin group have been differentiated. These are the Violin breccia, which lies along the San Gabriel fault, and the Hungry Valley formation, which consists of sandstone and conglomerate. The Violin breccia, here named for exposures on the divide between Violin and Palomas Canyons, has a stratigraphic thickness of about 27,000 feet, but extends along the strike for a maximum distance of only 4,000 feet! Throughout its extent it grades abruptly into finer-grained Ridge Basin rocks on the east. The breccia, which consists of a rubble of gneiss blocks as much as 6 feet in diameter in a muddy matrix, accumulated as talus or alluvial debris at the base of the San Gabriel fault scarp. The great thickness of the breccia, as well as the long span of time represented by its accumulation, bespeak intermittent or continuous rejuvenation of the fault scarp. Nearly continuous movement must have taken place along the San Gabriel fault from some time in the late Miocene until late in the Pliocene.

The record of nearly continuous deformation during later Tertiary time is unusually complete in the Ridge Basin area. As shown on the diagrammatic section, the Whitaker thrust is overlapped by lower Modelo rocks (upper Miocene). These are cut by the Canton fault, but this fault in turn is overlapped by middle Modelo units. On the east, several major faults affect the Martinez formation, but do not cut upper Miocene strata. The Clearwater fault has disturbed severely the lower Ridge Basin beds (lower Pliocene), but apparently dies out in the central part of the Ridge Basin. The Liebre fault, which played a significant role in defining the northeastern edge of the basin as judged from the coarseness of conglomerate and breccia that are exposed locally, is overlapped by Hungry Valley conglomerates (upper Pliocene). The San Gabriel fault on the northwest is overlapped by younger Hungry Valley beds (uppermost Pliocene). These beds were involved in folding and thrusting south of Frazier Mountain during Pleistocene time, and the still younger Frazier Mountain thrust has been sharply folded (Crowell, 1950, p. 1644). Even terrace deposits and alluvium have been grossly disturbed along the San Andreas fault zone, which truncates all the other structural features.

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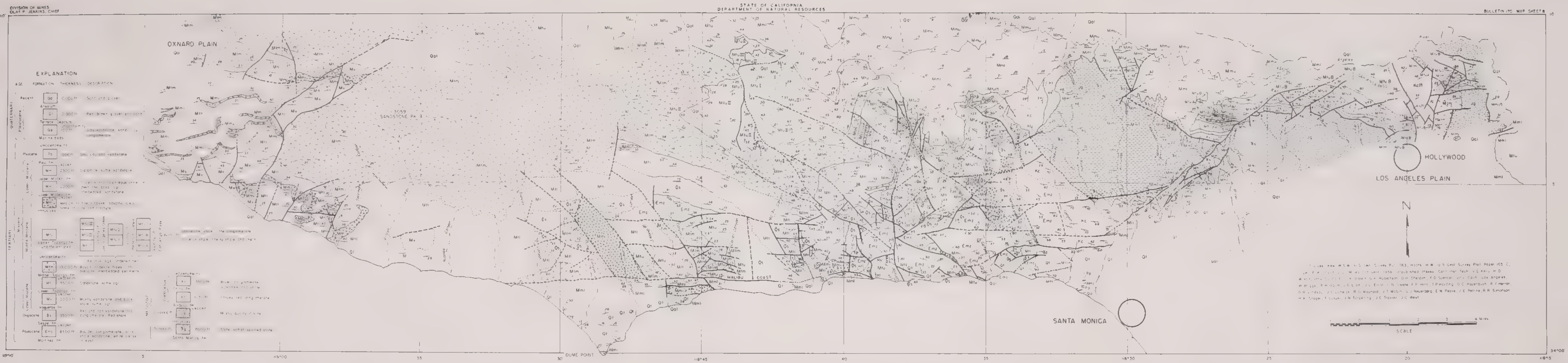

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 8

GEOLOGY OF THE SANTA MONICA MOUNTAINS, LOS ANGELES AND VENTURA COUNTIES

By Cordell Durrell *

INTRODUCTION

The Santa Monica Mountains are 3 to 13 miles wide, and extend from the Los Angeles River 45 miles eastward to the Oxnard Plain. They rise abruptly from the San Fernando Valley and the Los Angeles Plain, and from the Pacific Ocean farther west. The crest in the eastern part ranges in altitude from 1,200 to 1,500 feet, but is higher to the west, culminating in Sandstone Peak at 3,059 feet. The slopes are steep, and much of the area is covered with a dense growth of brush.

The present preliminary map, a compilation based on published reports of the U. S. Geological Survey (Hoots, 1931; Kew, 1924) and unpublished work of students, is not uniformly accurate, and some of it represents speculation on the part of the present author. Much remains to be accomplished before a satisfactory map and geologic history can be established for this area. Very little paleontologic work has been done, and the stratigraphic nomenclature is almost entirely unsatisfactory. The writer has drawn freely from the excellent report of Hoots for a description of the part of the range that lies east of Topanga Canyon.

STRATIGRAPHY

Mesozoic Rocks. The Santa Monica formation, which consists of metamorphosed black shale and graywacke of unknown thickness, crops out only in the eastern part of the range, although similar rocks are exposed on Santa Cruz Island 70 miles to the west on the same structural trend. The age of these rocks is provisionally set as Triassic by comparison with lithologically similar rocks of that age in the Santa Ana Mountains, 55 miles to the southeast. The Santa Monica formation was dynamothermally metamorphosed to slate and fine-grained schist, and then was intruded by batholithic masses of quartz dioritic magma. Contact metamorphism associated with these plutonic rocks yielded spotted slate and chiastolite slate. The intrusions are provisionally dated as Jurassic by comparison with those of the Sierra Nevada.

The metamorphic and plutonic rocks constitute the basement upon which a very thick section of Cretaceous and Cenozoic rocks was deposited after a long period of erosion.

The oldest of the unmetamorphosed sedimentary rocks are clayey red conglomerates, presumably of continental origin, of the Trabuco formation. These have not been dated by fossils, but have been assigned to the Upper Cretaceous because similar rocks lie conformably beneath marine Upper Cretaceous strata in the Santa Ana Mountains. In the Santa Monica Mountains the upper contact of the Trabuco probably is an unconformity. Deposition of the Trabuco beds was followed by accumulation of marine Upper Cretaceous epiclastic sediments of great but uncertain thickness

Cenozoic Rocks. Thick epiclastic sediments of the lower Eocene (Paleocene) Martinez formation rest unconformably on the Upper Cretaceous section, and are unconformably overlain by the Sespe formation. In the eastern part of the range, however, Eocene deposition is represented by a thin white arkose, which is overlain by beds younger than Sespe

The Sespe formation consists of red epiclastic sediments of continental origin. It is generally considered to range in age from upper Eocene through Oligocene into lower Miocene, but it has not been closely dated in the Santa Monica Mountains.

In the west end of the range, epiclastic marine sediments called Vaqueros (lower Miocene) are present, but their base is not exposed. In the central region the Sespe formation grades upward through alternations of unfossiliferous redbeds and fossiliferous gray and brown marine beds into the epiclastic Lower Topanga formation. This is well shown on the highway through Malibu Canyon. On the anticline west of the head of Topanga Canyon, this contact may be an unconformity, as faults that cut the Sespe strata do not enter the overlying Lower Topanga formation. Eastward from Stone Canyon, the Sespe formation is missing and the Lower Topanga strata rest on the Martinez formation.

The sediments of the Cretaceous, Eocene, Oligocene, and lowest Miocene (Vaqueros) formations could have been derived from crystalline basement rocks to the east or northeast. Westward from Point Dume the Lower Topanga formation contains fragments of bluish schist that could have been derived only from the south, as has been demonstrated for the San Onofre breccia of the same age (Woodford, 1925; Woodford and Bailey, 1928).

The epiclastic sediments of the Lower Topanga are succeeded by the submarine volcanic rocks and interbedded fossiliferous sediments of the Middle Topanga formation. The contact may be conformable or only slightly unconformable in the west, but it is markedly unconformable in the east near Cahuenga Pass, where the volcanic rocks rest on the Eocene Martinez formation. The volcanic rocks are present in two areas, which suggests two eruptive centers, but inasmuch as the upper contact is also an unconformity, the variations in thickness and the local absence of the formation may be due mostly or even solely to erosion.

The so-called Upper Topanga formation consists of several formations that have been distinguished in several areas, and that have not yet been correlated with one another. Some of the units are separated by unconformities, as in Brown Canyon where an angular discordance of 90 degrees is present. The older units are mostly fine-grained epiclastic accumulations, and the higher units contain more organic sediments, siliceous shale, and chert that closely resemble the strata of the overlying Modelo formation. Relizian and Luisian ages have been determined for the rocks at a few localities. Much work remains to be done on these beds.

Dikes, sills, and irregular intrusive masses of middle Miocene age cut the Upper Topanga formations and all older rocks, but do not cut rocks younger than the Upper Topanga. These igneous rocks are mostly basaltic, but some are of rhyolitic and trachytic composition. Medium- to fine-grained diabase is most abundant, and vesicular and amygdaloidal basalt breccias in both pipes and sills also have been recognized. It is difficult to distinguish the intrusive from the extrusive breccias except where upper contacts are well exposed. Many of the intrusive masses were emplaced along faults, as in the Topanga Canyon area.

The organic sediments and sandstones of the Lower Modelo formation transgress all older rocks, and thereby indicate intensive deformation prior to their deposition. This disturbance resulted in overturning of the Upper Topanga section north of Coldwater Canyon. Although the organic sediments of the Lower Modelo point to quiet conditions in the basin, the interbedded thick, coarse, and massive feldspathic sands perhaps indicate disturbances along or near the margins of the basin. The Upper Modelo diatomites were deposited in apparent conformity on the Lower Modelo section.

The marine Pliocene Pico formation and marine Pleistocene beds, which are restricted to a small area east of the mouth of Temescal Canyon, are each separated above and below by unconformities

Extensive continental Quaternary terrace deposits include thin marine sands at the base. These deposits have been incised and tilted, and they pass below sea level in the southern part of the city of Santa Monica.

STRUCTURE

The structural features in the Santa Monica formation and the plutonic rocks constitute a distinct problem not treated here. The Santa Monica formation has been folded into a complex anticline with west-trending axis and generally moderate dips. Abundant shear zones are certainly in part of pre-Trabuco age.

The dominant structural feature in the younger rocks of the range is a very complex west-trending anticline. Its south flank is missing in surface outcrop east of Coldwater Canyon, and again from Topanga Canyon west to Escondido Canyon. West of Escondido Canyon the anticlinal structure is evident as far as Little Sycamore Canyon, beyond which the axis of the fold lies beneath the sea. Superimposed minor folds trend northwest, and a northeast-trending fold is evident in the Eocene section just west of lower Topanga Canyon.

The south margin of the range in the central part is outlined by northeast- and east-trending faults. Similar faults no doubt continue westward beneath the sea, and eastward beneath an alluvial cover. No such boundary faults are known on the north margin of the range. Both northeast- and northwest-trending fault systems are well developed, and north-trending faults also are present. Both normal and reverse movements are known, and lateral movements are highly probable. Successive movements of different character on the same fault are illustrated by the Benedict Canyon fault, which was probably established in pre-Cretaceous time. It shows a 1.5-mile horizontal offset of the pre-Modelo strata, which moved southwest or down on the northwest side. In contrast, the post-Modelo movement was down on the southeast side.

TECTONIC HISTORY

Pre-Upper Cretaceous tectonic activity that affected the Santa Monica formation included both folding and faulting. Metamorphism and invasion by magma also occurred.

Folding of later date is indicated by each of the numerous unconformities in the younger rocks, and tectonic activity appears to have been nearly continuous throughout Tertiary and Quaternary time. Faulting accompanied most of these disturbances. Although it has not been proven, the Cretaceous rocks probably were faulted as well as folded prior to deposition of the Martinez strata, and this formation probably was in turn faulted at the time of the intense disturbance that preceded deposition of the Sespe strata. The Sespe formation is cut by faults that do not enter the overlying Lower Topanga section, and the youngest of the Upper Topanga formations lies across faults in slightly older beds. The Modelo formation is unaffected by many faults that cut underlying rocks, but it also is faulted, in many places by renewed movement on older breaks. The Pliocene and Pleistocene sediments also are faulted, and only the Quaternary terrace deposits are not known to be so affected.

The Santa Monica Mountains represent a large part of a trough in which sediments younger than the Santa Monica formation accumulated to an estimated thickness of nearly 50,000 feet. Although such a thickness does not and never did exist in any one place, a substantial part of it must have been present in the central part of the range, as the Upper Topanga and the Modelo formations formerly extended across the site of the mountain range. Perhaps most of the epiclastic sediments were derived from the east and northeast, and some certainly were derived from lands to the south that no longer exist.

It is impossible yet to establish the time of maximum intensity of tectonic activity in the area, but very intense disturbances preceded deposition of the Sespe formation, of the Upper Topanga formations, and of the Modelo formation. It is probable that post-Modelo deformation was less severe, and that more recent activity was still less intense.

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OLAF P. JENKINS, CHIEF

STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

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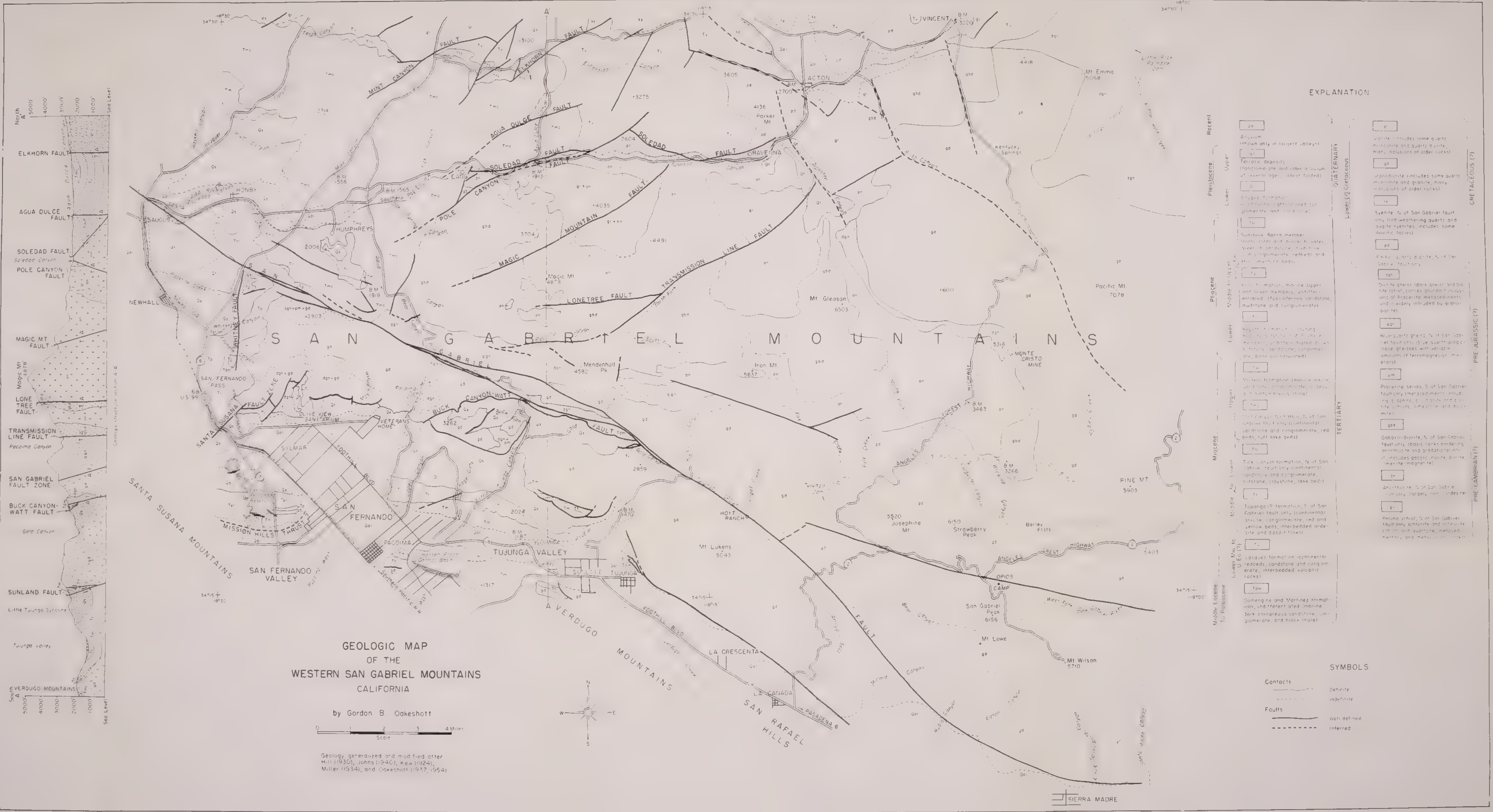
North A'
5000'
4000'
3000'
2000'
1000'
Sea Level
ELKHORN FAULT
AGUA DULCE FAULT
SOLEDAD FAULT
Soledad Canyon
POLE CANYON FAULT
MAGIC MT FAULT
Magic Mt 4878
LONE TREE FAULT
TRANSMISSION LINE FAULT
Pacoima Canyon
SAN GABRIEL FAULT ZONE
BUCK CANYON-WATT FAULT
Gold Canyon
SUNLAND FAULT
Little Tujunga Syncline
Tujunga Valley
VERDUGO MOUNTAINS
South A
Geologic structure section A-A'
A'
A
SAN GABRIEL MOUNTAINS
MINT CANYON FAULT
ELKHORN FAULT
AGUA DULCE FAULT
SOLEDAD FAULT
POLE CANYON FAULT
MAGIC MOUNTAIN FAULT
LONETREE FAULT
TRANSMISSION LINE FAULT
WHITNEY FAULT
SAN GABRIEL FAULT
BUCK CANYON-WATT FAULT
SANTA SUSANA FAULT ZONE
MISSION HILLS THRUST
VINCENT
ACTON
RAVENNA
Parker Mt
Mt Emma 5068
Kentucky Springs
Pacific Mt 7078
Mt Gleason 6503
Magic Mt 4878
Mendenhall Pk 4582
Iron Mt 5637
MONTE CRISTO MINE
PINE MT 5903
Josephine Mt 5520
Strawberry Peak 6150
Barley Flats
Mt Lukens 5043
HOYT RANCH
OPIDS CAMP
San Gabriel Peak 6156
Mt Lowe
Mt Wilson 5710
SIERRA MADRE
SAUGUS
HONBY
HUMPHREYS
NEWHALL
SAN FERNANDO PASS
US 99
OLIVE VIEW SANITARIUM
VETERANS HOME
SYLMAR
SAN FERNANDO
PACOIMA
TUJUNGA VALLEY
SUNLAND
TUJUNGA
SAN FERNANDO VALLEY
SANTA SUSANA MOUNTAINS
VERDUGO MOUNTAINS
SAN RAFAEL HILLS
LA CRESCENTA
LA CANADA
PASADENA
ANGELES FOREST HIGHWAY
ANGELES CREST HIGHWAY
FOOTHILL BLVD
Mint Canyon
Soledad Canyon
Bouquet Canyon
Placerita Canyon
Pacoima Canyon
Big Tujunga Canyon
Arroyo Seco
West Fork San Gabriel River
Eaton Canyon
Santa Anita Canyon
34°30'
118°30'
118°15'
118°00'
34°15'
N
S
E
W
0
1
2
3
4 Miles
Scale
EXPLANATION
Recent
Qa
Alluvium (shown only in largest valleys)
Pleistocene
Upper
Qt
Terrace deposits (conglomerate and older alluvium of several ages, oldest folded)
Lower
Qs
Saugus formation (continental light-colored conglomerate and sandstone)
QUATERNARY
Pliocene
Middle to Upper
Tss
Sunshine Ranch member (continental and brackish-water, greenish sandstone, mudstone with conglomerate, redbeds and thin limestone beds)
Tp
Pico formation, marine Upper and Lower members, undifferentiated (fossiliferous sandstone, mudstone and conglomerate)
Lower
Tr
Repetto formation, including Repetto and Elsmere members, undifferentiated (brown siltstone, sandstone, conglomerate, base oil-saturated)
Miocene
Upper
Tm
Modelo formation (marine arkose, sandstone, conglomerate, siliceous and diatomaceous shale)
Tmc
Mint Canyon formation, N of San Gabriel fault only (continental sandstone and conglomerate, red beds, tuff lake beds)
Middle to Lower
Ttc
Tick Canyon formation, N of San Gabriel fault only (continental sandstone and conglomerate, siltstone, claystone, lake beds)
Tt
Topanga (?) formation, S of San Gabriel fault only (continental arkose, conglomerate, red and yellow beds, interbedded andesite and basalt flows)
Lower Mio to U Eo (?)
Tv
Vasquez formation (continental redbeds, sandstone and conglomerate, interbedded volcanic rocks)
Middle Eocene to Paleocene
Tdm
Domengine and Martinez formations, undifferentiated (marine dark calcareous sandstone, conglomerate, and black shale)
TERTIARY
Lower (?) Cretaceous
qd
Diorite (includes some quartz monzonite and quartz diorite, many inclusions of older rocks)
gd
Granodiorite (includes some quartz monzonite and granite, many inclusions of older rocks)
sy
Syenite, N of San Gabriel fault only (red-weathering quartz and augite syenites, includes some dioritic facies)
CRETACEOUS (?)
pd
Parker quartz diorite, N of San Gabriel fault only
dgn
Diorite gneiss (dark gneiss and biotite schist, carries abundant inclusions of Placerita metasediments and is widely intruded by granodiorite)
qgn
Blue-quartz gneiss, N of San Gabriel fault only (blue quartz-plagioclase gneisses with variable amounts of ferromagnesian minerals)
PRE-JURASSIC (?)
pm
Placerita series, S of San Gabriel fault only (metasediments including graphite, sillimanite and biotite schists, limestone and dolomite)
gbd
Gabbro-diorite, N of San Gabriel fault only (basic rocks bordering anorthosite and gradational into it, includes gabbro, norite, diorite, ilmenite-magnetite)
an
Anorthosite, N of San Gabriel fault only (largely anorthosite)
pr
Pelona schist, N of San Gabriel fault only (chlorite and actinolite schists and quartzite, metasediments, and metavolcanic rocks)
PRE-CAMBRIAN (?)
SYMBOLS
Contacts
Definite
Indefinite
Faults
Well defined
Inferred

GEOLOGIC MAP OF THE WESTERN SAN GABRIEL MOUNTAINS CALIFORNIA

by Gordon B. Oakeshott

Geology generalized and modified after Hill (1930), Johns (1940), Kew (1924), Miller (1934), and Oakeshott (1937, 1954)

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 9

GEOLOGY OF THE WESTERN SAN GABRIEL MOUNTAINS, LOS ANGELES COUNTY

By Gordon B. Oakeshott *

INTRODUCTION

The accompanying geologic map covers approximately the western half, or about 550 square miles, of the San Gabriel Mountains, one of the prominent east-west ranges in the Transverse Range province of southern California. The range is scored by steep, narrow canyons, and also includes broader summit areas that retain elements of an older erosion surface. Altitudes of about 1,000 feet in the adjacent San Fernando Valley increase generally eastward through the range to Pacifico Mountain, 7,078 feet, the highest point in the map area.

Initial uplift of the San Gabriel Mountains probably took place in upper Eocene-Oligocene time, and renewed uplift and local deformation by folding and faulting took place in upper Miocene time. The major epoch of intense folding and faulting was much more recent and has been dated as middle Pleistocene. Continued movements on already-established faults, renewed near-vertical uplift, and deep erosion developed the present topography during late Quaternary time.

PRE-TERTIARY ROCKS

The oldest geologic units in the western San Gabriel Mountains and vicinity are the Placerita series, exposed only south of the San Gabriel fault, and the Pelona schist, exposed only north of this fault in the extreme northwest part of the map area. The Placerita series appears within younger igneous rocks as scattered roof pendants of once-extensive marine limestone, dolomite, shale, and sandstone, now chiefly crystalline limestone, schists, and quartzite. These rocks are best seen just west of Little Tujunga Canyon and along upper Placerita Creek. The rocks mapped as "diorite gneiss" include a variety of dark gneisses, metadiorites, and schists, among them hornblende diorite, hornblende quartz diorite, and biotite schists. Some of these are intrusive into the Placerita series and are closely associated with it west of Little Tujunga Canyon. Somewhat similar dark gneisses, also mapped as diorite gneiss, border anorthosite east of Mt. Gleason and crop out in the northeastern part of the map area. The intrusive diorite gneiss is well exposed along the Little Tujunga road at its junction with Gold Creek. The Pelona schist in the area mapped consists of chlorite and actinolite schists and quartzite that are cut by numerous quartz veins; this formation has been mapped and described by Simpson (1934).

No conclusive evidence of the ages of the Placerita series and diorite gneiss has been obtained. However, similarity of the Placerita limestone to the fossiliferous Furnace limestone (Carboniferous) in the San Bernardino Mountains suggests a possible late Paleozoic age: The Pelona schist is pre-Cretaceous, and may be as old as pre-Cambrian.

A gneiss of unusual appearance, consisting of bluish quartz, highly altered plagioclase, perthite, and biotite, borders anorthosite and related rocks just north of the San Gabriel fault from Trail Canyon to Bear Canyon. It is well exposed along the Little Tujunga road. Its contacts are faulted and obscure, but it is possible that this gneiss is a deuterically altered border facies of the anorthosite.

In the central part of the range is approximately 50 square miles of gray to white andesine anorthosite, together with a comparable area of closely related rocks that include gabbro, gabbro-norite, norite, hornblende diorite, altered pyroxenite, and masses of ilmenite-magnetite rocks.

The anorthosite proper ranges in texture from medium- to extremely coarse-grained. Its plagioclase ranges in composition from oligoclase to labradorite, and averages basic andesine. The anorthosite is gradational into the related rocks noted above, and it has been intricately intruded by muscovite-biotite granite along its northern and eastern margins. There is little evidence to indicate the age of the anorthosite-gabbro group of rocks, except that they have been intruded by granitic rocks that probably are similar in age to those of the southern Sierra Nevada and Peninsular Ranges (Cretaceous?). Excellent exposures of anorthosite and related rocks, together with the granitic rocks, can be seen along the Angeles Forest Highway in Mill Creek and along the highway and railroad between Lang and Ravenna in Soledad Canyon.

Most widely distributed are the Cretaceous (?) granitic rocks, which include biotite-muscovite granite, granite pegmatite, quartz monzonite, and hornblende quartz diorite. Biotite granodiorite, coarse-grained and slightly gneissoid, predominates south of the San Gabriel fault and north of that fault east of Gold Creek, and hornblende-biotite quartz monzonite is a common facies. Medium-grained pinkish and gray muscovite-biotite granite, commonly gneissoid, predominates along the northern margin of the anorthosite mass in the Soledad Canyon area and in upper Mint Canyon. Dikes of pegmatite, aplite, and lamprophyre are common in the granitic rocks. Inclusions of older rocks, mainly of obscure origin, are widely distributed in all the granitic rocks.

Limited exposures of the Parker quartz diorite (Miller, 1934) are present north of Ravenna, and exposures of syenite are present at the northern border of the map area. The syenite contains augite, some quartz, and commonly much microperthite. It has been described by Webb (1938). The ages of these rocks are unknown, but they probably are related to the Cretaceous (?) granitic group.

TERTIARY AND QUATERNARY ROCKS

The structural and topographic high of the San Gabriel Mountains is flanked on the northwest, west, and southwest by many thousands of feet of marine and continental sedimentary formations, with intercalated volcanic rocks, which were deposited at the eastern end of the Ventura basin. The oldest of these formations is represented by remnants of well-indurated dark marine sandstone, conglomerate, and shale of the Paleocene Martinez stage, which are exposed as slivers along the San Gabriel fault zone. A small patch of sandstone and conglomerate of the middle Eocene Domengine stage is preserved in Elsmere Canyon. These strata lie unconformably beneath lower Pliocene sediments. Martinez Meganos, and Domengine strata have been encountered in wells in the Placerita area, south of the San Gabriel fault.

Exposed in a large area along the northern margin of the mountains is more than 9,000 feet of highly-colored continental sediments with several thousand feet of intercalated basaltic volcanic rocks. These constitute the upper Eocene-Oligocene (?) Vasquez formation (Jahns, 1940), which may well be equivalent to the Sespe formation farther west. The Vasquez formation is unconformably overlain by 600 feet of coarse continental beds of the middle to lower Miocene Tick Canyon formation, which are exposed in a limited area in the vicinity of Tick Canyon and upper Mint Canyon (Jahns, 1940). Very small masses of redbeds and basaltic volcanic rocks are exposed in the Pacoima Hills and at points north of the Tujunga Valley; these have been mapped as Topanga (?) formation, and may constitute a Tick Canyon equivalent south of the San Gabriel fault. More than 4,000 feet of fluviatile and lacustrine beds of conglomerate, sandstone, siltstone, and tuff of the upper Miocene Mint Canyon formation crop out widely on the north side of the range west of Agua Dulce Canyon. They overlie the Tick Canyon formation unconformably.

Approximately 1,700 feet of marine arkose, conglomerate, and siliceous shales of the upper Miocene Modelo formation crop out along the northern margin of the San Fernando Valley. This formation unconformably overlies Mint Canyon beds in Bouquet Canyon, and also has been encountered at depth in the western part of the Placerita oil field.

Marine lower Pliocene brown conglomerate and sandstone beds of the Repetto formation crop out along the northern margin of the San Fernando Valley, reaching their maximum thickness of 3,000 feet at Lopez Canyon. A highly fossiliferous and oil-saturated basal sandstone (Elsmere member) of this formation, conformably overlain by siltstone, crops out north of the Santa Susana thrust as far as Whitney Canyon, and is overlapped by the marine upper Pliocene clastic sediments of the Pico formation. Remnants of the Repetto formation appear north of the San Gabriel fault west of Sand Canyon, but there the overlying upper Pliocene section is nonmarine, and is represented only by conglomerate, greenish sandstone, and mudstone of the Sunshine Ranch member of the Pico formation. The Sunshine Ranch member reaches its maximum thickness of 3,000 feet on the west side of San Fernando Reservoir, where it lies unconformably on middle Pliocene fossiliferous calcareous sandstone of the Lower Pico member of the Pico formation.

The continental lower Pleistocene Saugus formation, consisting of poorly sorted, light-colored conglomerate and coarse sandstone, commonly crossbedded, overlaps all of the older formations and lies on the Mint Canyon formation west of Mint Canyon and on the crystalline rocks in upper Little Tujunga Canyon. The thickness of the Saugus gravels in the northwestern end of the San Fernando Valley is more than 6,000 feet.

An excellent and easily observed section of Modelo, Repetto, Pico, Sunshine Ranch, and Saugus beds is exposed in the great road cuts of State Highway 7 (Sepulveda Blvd.) on the east side of San Fernando Reservoir. A section across the San Gabriel fault and Placerita oil field can be followed by continuing north on U. S. Highway 6 (Sierra Highway).

Remnants of older alluvial deposits are widely distributed at several different levels. These generally consist of coarse, poorly sorted, brown-weathering fanglomerate, gravel, and sand. The oldest of such deposits, like that just west of U. S. Highway 6 and south of the San Gabriel fault, have been folded and faulted. They lie on the Saugus formation with a great angular unconformity.

TERTIARY AND QUATERNARY STRUCTURAL FEATURES

Faulting. The major structural feature of the western San Gabriel Mountains is the San Gabriel fault, a San Andreas-type rift that extends obliquely across the western part of the range to a possible junction with the San Andreas fault near Frazier Mountain, about 40 miles to the northwest. The San Gabriel fault system comprises (1) a principal series of steeply north-dipping shear planes, along the San Gabriel fault proper, that trend N. 35°-75° W. and show right-lateral movement; (2) a series of subordinate Garlock-type faults, in the north block, that trend N. 30°-65° E. and show left-lateral movement; and (3) a group of north-dipping reverse faults, in the south block, similar to the Santa Susana thrust northwest of San Fernando.

The important east-trending Soledad fault is a north-dipping normal fault that marks the contact in Soledad Canyon between the San Gabriel crystalline massif on the south and the continental sediments of the eastern end of the Ventura basin (Soledad basin) on the north. The Soledad fault has been apparently offset 1.4 miles by left-lateral movement on the Pole Canyon fault.

Movement on the principal faults dates back, with reasonable certainty, to upper Miocene time, but may have originated as early as upper Eocene or Oligocene time. Displacements of marine Pliocene and continental lower Pleistocene formations and offsets of major stream courses give evidence for post-Pliocene right-lateral movement of more than 2½ miles along the San Gabriel fault, at least 1½ miles of which is probably of post-lower Pleistocene age. The left-lateral faults of the north block show offsets of formational contacts and structural features ranging from 0.4 mile to more than 2 miles. The reverse faults of the south block show essentially dip-slip movements ranging from a few hundred feet to more than 2,000 feet; some of these faults are offset by the slightly younger San Gabriel fault.

Folding. Unconformities between the successive Tertiary and Quaternary formations show that mild orogenic movements took place locally at various times during the Cenozoic area, but the mid-Pleistocene orogenic epoch overshadowed all of the others in intensity. Folding in the region is closely associated with faulting, in origin as well as in time, and the axes of the principal folds are roughly parallel to the major fault zones. A series of northeast-trending folds in the Tertiary continental sediments north of the Santa Clara River is cut at low angles by left-lateral faults such as the Mint Canyon, Elkhorn, and Agua Dulce.

Stratified rocks in the San Gabriel fault zone generally have been compressed into tight, very steeply dipping folds. The principal fold on the south side of the range is the Little Tujunga syncline, whose axis parallels the San Gabriel fault and lies about 2½ miles southwest of it. Lower Pleistocene Saugus beds locally have been overturned along the north limb of this syncline. Some of the reverse faults, such as the Buck Canyon-Watt fault, may have been folded; also, in some places, later faulting clearly has cut folds.

Stresses that resulted in some deformation in the western San Gabriel area intermittently during the Tertiary period reached their culmination with intense folding and faulting in mid-Pleistocene time. Folding, faulting, and uplift continued more mildly during late Pleistocene time. The pattern and character of folding and faulting are consistent with a stress-strain system involving crustal shortening in a north-south direction.

MINERAL DEPOSITS

Borates. Colemanite deposits in the Vasquez formation in Tick Canyon were worked from 1907 until 1920, when the Pacific Coast Borax Company purchased the property.

Gold. Small amounts of both placer and lode gold have been produced from many deposits in the area. One of the best known mines is the Monte Cristo, a lode mine east of Angeles Forest Highway and Mill Creek. Several lode mines in the Acton district have yielded a moderately large aggregate production over a long period of time.

A plaque indicating the discovery of gold in 1842 has been placed in Placerita Canyon a short distance west of Sand Canyon.

Ilmenite. The numerous titaniferous magnetite bodies in anorthosite and gabbro of the San Gabriel Mountains represent the largest reserves of titanium in California. Production has been small, all of it during the past few years from sands in Bear Canyon.

Petroleum. The principal mineral product of the western San Gabriel Mountains area has been petroleum derived from the Placerita oil field, Elsmere Canyon area, and Whitney Canyon area at the extreme western end of the range. A little high-gravity oil has been produced from the Placerita schist area in the San Gabriel fault zone 2½ miles east of the Placerita oil field. All these areas have been abandoned except the Placerita field, which produced 1,887,000 barrels of 21.0° gravity oil and 1,571,000 barrels of 12.7° gravity oil in 1952.

Rock, Sand, and Gravel. More than 330,000 cubic yards of "granite" (biotite granodiorite and hornblende-biotite quartz monzonite) were taken from a quarry on the south side of Gold Creek to build the Hansen Flood Control Dam during the period 1938-1940. "Decomposed granite" (gneissic quartz diorite) has been quarried in the Pacoima Hills. The City Rock Company is operating a gravel pit in Tujunga Wash below Sunland, and produces about 500,000 tons a year. The MacArthur gravel pit, in Soledad Canyon, is currently in operation.

Miscellaneous Minerals. Other mineral production includes anorthosite for poultry grits (Soledad Canyon), graphite (upper Kagel Canyon) limestone and dolomite (between Little Tujunga and Kagel Canyons), diatomaceous shale (north of Tujunga Valley), and volcanic tuff (upper Bouquet Canyon) for chinchilla dust. Graphite and limestone have not been mined for many years.

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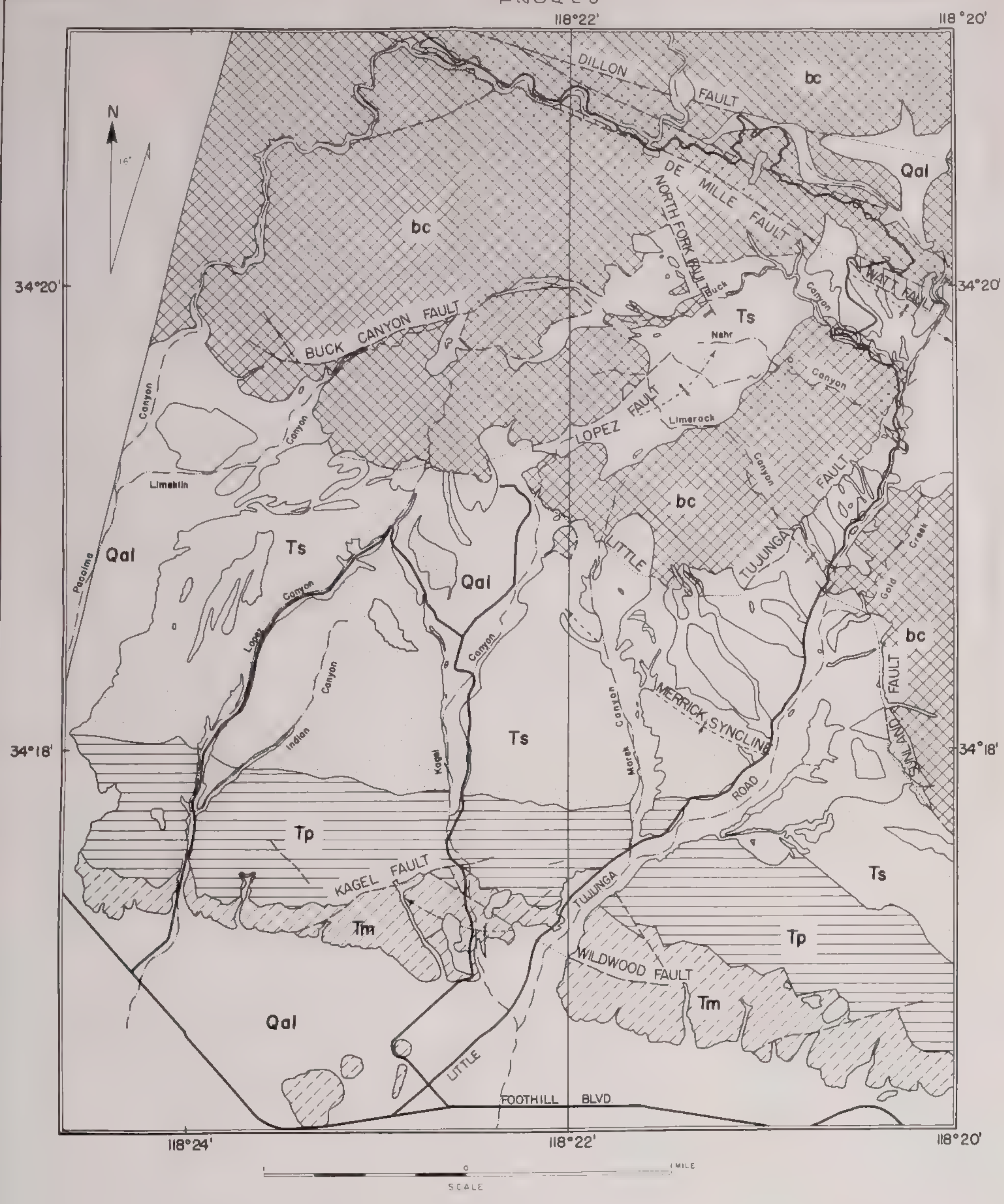
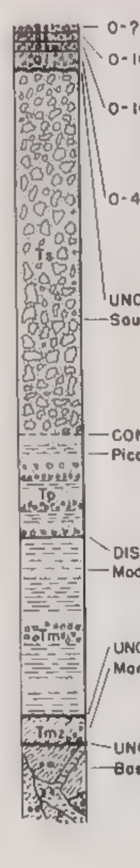


LEGEND OF GEOLOGICAL MAP

- Fault
- Syncline showing plunge
- Anticline
- Stream
- Roads

Qal	Recent (and Pleistocene ?)— Alluvium and landslides
Ts	Plio-Pleistocene—Saugus fm.
Tp	Pliocene – Pico fm
Tm	Miocene – Modelo fm
Tmz	Paleocene-Martinez fm
bc	Pre-Cretaceous – Basement complex

STRATIGRAPHIC COLUMN



0-?Feet Recent alluvium in valleys, talus slopes, landslides

0-100' Kagel alluvium, Pleistocene or Recent fans which once filled several canyons.

0-100' Beehive Mesa Alluvium, Pleistocene or Recent, bedded, dark fan remnants. May be same age as Kagel or Lopez

0-400' Lopez Alluvium, Pleistocene or Recent An older, higher fan than any of the others except possibly the Beehive Mesa.

UNCONFORMITY

Saugus formation At least 7800' of red and white, continental, arkosic sandstone and conglomerate. Lower Pleistocene to Upper Pliocene

CONFORMABLE CONTACT

Pico formation 0-2500' of gray, tan or brown marine conglomerate and sandstone with lesser amounts of siltstone and shale. Pliocene.

DISCONFORMITY

Modelo formation 0-3700+' of gray-tan marine silty shale, white to tan sandstone and conglomerate Upper Miocene

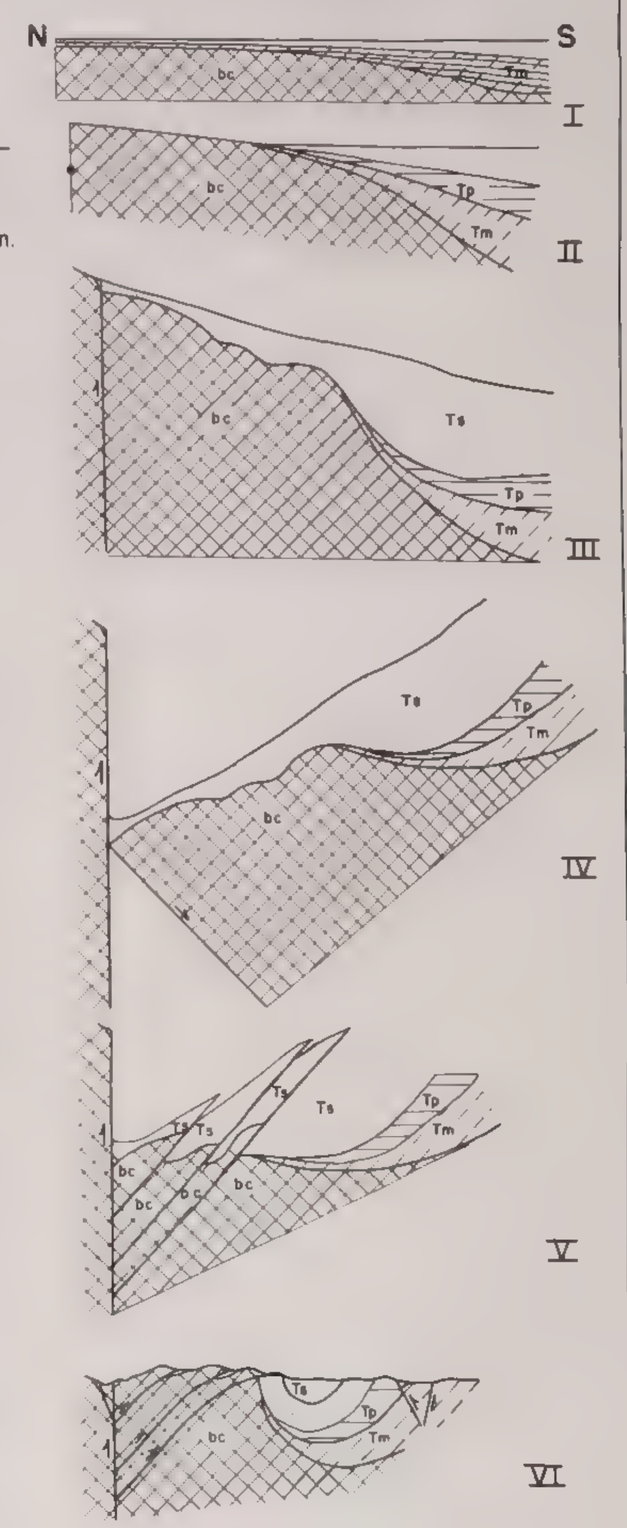
UNCONFORMITY (Not exposed)

Martinez formation. Unknown thickness of Paleocene marine, mottled conglomerate, tan siltstone, and black shale

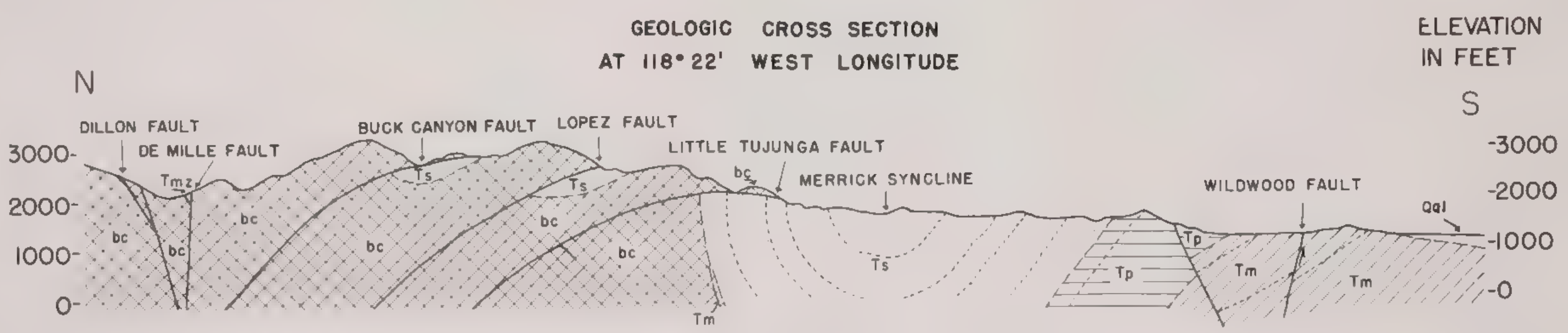
UNCONFORMITY (Not exposed)

Basement complex
- pm - Placerita metasediments
- rd - Rubio diorite & hornblendite.
- eg - Echo granite.
- ad - Gabbroic & dioritic facies of anorthosite.

SEQUENCE OF EVENTS IN THE DEVELOPMENT OF THE PRESENT STRUCTURE OF THE LITTLE TUJUNGA REGION



GEOLOGIC CROSS SECTION AT 118°22' WEST LONGITUDE



DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 10

GEOLOGY OF THE LITTLE TUJUNGA AREA, LOS ANGELES COUNTY

By Benjamin F. Howell, Jr.*

Within the Little Tujunga area, two of the major fault systems of southern California, the San Gabriel and the Sierra Madre-Santa Susana-San Cayetano, make their closest approach to each other at the surface, and possibly intersect at a shallow depth. The area lay at or close to the northern edge of the Los Angeles depositional basin during most of the Tertiary period. A part of the land mass that may have supplied some of the sediments to the basin crops out here, and some of the basin strata lie with depositional contact upon these older crystalline rocks.

Geologic History. The oldest event recorded in this area is the deposition of the Placerita sediments, possibly in Paleozoic time. These included both limestone and clastic detritus. At this time the region was part of a large depositional basin. The Placerita section was intruded later by a succession of igneous rocks ranging from granite to gabbro. The sediments were intensely metamorphosed at this time, and may also have been metamorphosed prior to the earliest episode of intrusive activity.

Subsequently the region was eroded, although no remnants of the erosion surface have been preserved. By Paleocene time, the region had become submerged. Shale, siltstone, and sandstone of the Martinez formation reflect deposition under marine conditions, and now are preserved in wedges dropped between branches of the San Gabriel fault. The predominance of fine-grained sediments suggests a widespread inundation by the sea.

The next younger unit, the Miocene Modelo formation, lies on a relatively smooth surface of basement rocks, indicating that its deposition was preceded by a considerable period of erosion. The preservation of wedges of Martinez strata in the fault zone indicates that movement on this fault began during this interval. The oldest Miocene rocks are largely fine-grained, which may indicate that they were deposited at a moderate distance from the shore, but coarseness increases toward the top of the section, as though the shore line were approaching the Little Tujunga region. A brief emergence between Miocene and Pliocene times is indicated by a disconformity between the Modelo and the overlying Pico beds. The contact is irregular, indicating that erosion did not have time to level the old land surface. The Pico strata show little or no angular discordance with the Modelo strata in the Little Tujunga region, although less than a mile south of the area a marked difference in dip is observable.

The Pico sediments are mainly very coarse grained, and do not extend as far north as the Modelo beds. This suggests that a Pliocene shore line lay just south of the San Gabriel fault. Periodic movements on this break may have been responsible for deposition of the many sequences of conglomerate, sandstone, and siltstone present in the Pico section.

As the end of the Pliocene epoch approached, the sea was filled with sediments, and a continuous transition to terrestrial deposition occurred. A huge alluvial deposit (the Saugus formation) was built up against the rising mountain front in the central part of the area. More than 7,800 feet of fanglomerate is exposed, but it is improbable that strata of this thickness covered any one point. The formation probably lapped up onto the mountain front.

The top of the Saugus section has been eroded off. The diastrophism that raised the mountains along which this fan was formed probably culminated in late Pliocene time. The resulting structural features were of three types: (1) the steep normal and reverse faults of the San Gabriel system, which raised the basement complex to the north and also may have had a strong strike-slip component; (2) the five reverse and thrust faults of the Sierra Madre system to the south (Maple Canyon, Buck Canyon, Lopez, Little Tujunga, and Sunland faults), which slid blocks of basement rocks out over Saugus sediments; and (3) the Merrick syncline and other folds in the softer, more pliable sedimentary rocks.

This sequence of events is illustrated in the accompanying structure sections. The last of these, section VI, was made by projecting the north-south structure section made along 118°22' longitude to greater depths. In section V, each block has been straightened out as it would have appeared before flexing bent its upper end. In section IV, the shifted blocks have been restored to their unfaulted positions. It is thus seen that a 45° rotation of the block of sediments of section III can be expected to yield the distribution of rocks now exposed in the Little Tujunga area. The entire original block need not have been tilted; only the end adjoining the San Gabriel fault need have been depressed. The normal faults in the southern part of the mapped area may have resulted from cracking due to stretching of the surface as the north edge of the block sank. It is likely that more faults are present in the basement rocks than are shown at the surface, the motion being absorbed by folding in the overlying sediments. This theory of fault formation is discussed in greater detail elsewhere (Howell, 1949).

Following the post-Saugus orogeny, which formed the present San Gabriel Mountains, erosion developed the present drainage pattern. At least three ages of alluvium show that there have been several Pleistocene or Recent rejuvenations of uplift in the area. The present cycle is one of erosion throughout most of the area, although modern alluvium is being deposited in Big Tujunga and Pacoima Canyons. In the smaller canyons, most or all of the valley-bottom alluvium moves during periods of major floods.

Typical Exposures. A typical cross section of the formations and structural features in the area can be seen by driving north on Little Tujunga Road. As one enters the mouth of Little Tujunga Canyon, north-dipping beds of the Modelo formation appear on either side, but are best exposed on the east. The lower part of this formation is largely shale, but the percentage of coarse clastic material increases upward. The bottom of the Pico formation is marked by a disconformable basal conglomerate that is well exposed in a gully on the east side of the canyon. This is in marked contrast to the area half a mile to the south, where a marked angular unconformity separates these formations. Lithologically, the Pico is very similar to the Modelo, except that it is generally coarser. It grades continuously into the overlying terrestrial arkosic sandstones of the Saugus formation. The contact can be identified by a bed of white sandstone that crops out at a bend in the road 2,000 feet beyond the mouth of Marek Canyon.

Farther north the dip of the Saugus beds reverses in the Merrick syncline. The slopes on either side of the canyon here are largely masked by the little weathered Kagel alluvium, which once choked all the canyons of the area. Patches of the older Lopez alluvium occur on ridge crest between here and Marek Canyon, as well as to the west, but they are not visible from the road.

At a slight rise in the road 7,000 feet beyond the exposed top of the Pico formation, the contact of the Saugus beds on the basement rocks is exposed. Just south of this exposure, the Saugus formation is considerably sheared. This is the west end of the Sunland reverse fault, a branch of the Sierra Madre fault system. The total displacement here probably does not exceed a few hundred feet, but it increases rapidly to the southeast. Immediately north of this point the dip of the Saugus section is reversed, and the beds can be seen dipping off the eastern fault block and under the basement rocks to the west. Many exposures of the Saugus-basement contact occur along the valley from here to the point where a side road crosses the wind gap into Gold Canyon. The outcrops of basement rocks here show typical lithologic and structural complexities.

The wind gap is probably a result of stream piracy. Many of the present streams, such as Buck Creek, the upper part of Gold Creek, and the stretch of Little Tujunga Creek just discussed, lie along the contact between the Saugus formation and the basement rocks, and owe their position to migration down the dip slope of the harder rocks as the soft sediments were cleaned off. It is probable that Little Tujunga Creek once joined Gold Creek just east of the present wind gap, and that its course became entrenched in the basement rocks there. A later rejuvenation allowed a lower tributary to capture the upper part of Little Tujunga Creek. Similar piracy has been common along the headwarters of Nehr and Limerock Creeks.

One of the best exposures of the Little Tujunga fault is in Nehr Canyon. The dip is steep, and reverse movement is shown. The fault dies out quickly on entering the Saugus section, which dips off the north and west sides of this block, as in the Sunland block.

On leaving Buck Canyon, the road rises to the top of Beehive Mesa. This is capped by an alluvium different from that in any other part of the area. In large part it is finer grained, distinctly bedded, and has a characteristic brown color.

As the road swings east along the mountain front, it crosses the Watt and De Mille faults, and a wedge of Martinez shales and sandstones lies between these breaks. A similar wedge is exposed in Pacoima Canyon to the west. The extreme fracturing of the basement complex here is typical of the rocks within the San Gabriel fault zone. The north branch of this great break, the Dillon fault, is best exposed on the hillside north of the first bend in the road after it starts to leave Pacoima Canyon just outside the area shown on the map. The fault also occupies the divide where the road crosses from the Little Tujunga to the Pacoima watershed. The several branches of the San Gabriel fault dip toward one another, as if merging at depth, and the De Mille branch is nearly vertical. It has been suggested that the San Gabriel fault, like the San Andreas, is predominantly a strike-slip fault. If this is true, and if the offset of Pacoima Creek results from this motion, the northeast block would appear to have moved southeast with respect to the other block. This right-lateral movement is similar to that along the San Andreas fault. There is no evidence that any of the faults in this area have been active since the end of Saugus time.

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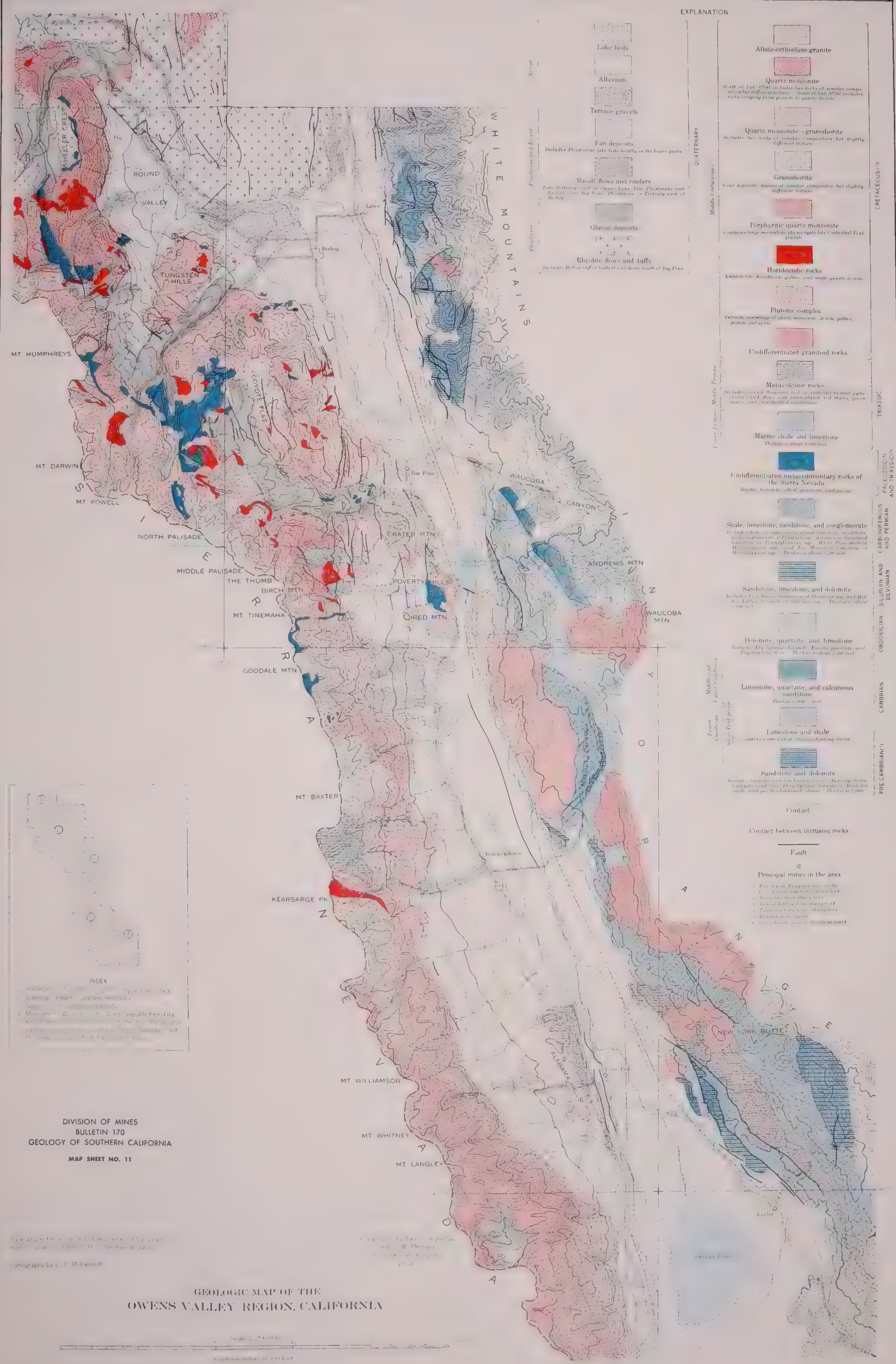
DEPARTMENT OF NATURAL RESOURCES

UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BULLETIN 170 MAP SHEET 11


EXPLANATION
Lake beds
Alluvium
Terrace gravels
Fan deposits
Includes Pleistocene lake beds locally in the lower parts
Basalt flows and cinders
Glacial deposits
Rhyolite flows and tuffs
Recent
Pleistocene and Recent
Pleistocene
QUATERNARY
Albite-orthoclase granite
Quartz monzonite
Quartz monzonite—granodiorite
Includes two rocks of similar composition but slightly different texture
Granodiorite
Four separate masses of similar composition but slightly different texture
Porphyritic quartz monzonite
Contains large microcline phenocrysts like Cathedral Peak granite
Hornblendic rocks
Plutonic complex
Intricate assemblage of quartz monzonite, diorite, gabbro, granite and aplite
Undifferentiated granitoid rocks
Middle Cretaceous
CRETACEOUS(?)
Metavolcanic rocks
Marine shale and limestone
Lower Triassic
Middle Triassic
TRIASSIC
Undifferentiated metasedimentary rocks of the Sierra Nevada
Marble, hornfels, schist, quartzite, and gneiss
PALEOZOIC(?) AND TRIASSIC(?)
Shale, limestone, sandstone, and conglomerate
CARBONIFEROUS AND PERMIAN
Sandstone, limestone, and dolomite
SILURIAN AND DEVONIAN
Dolomite, quartzite, and limestone
Includes Ely Springs dolomite, Eureka quartzite, and Pogonip limestone
ORDOVICIAN
Limestone, quartzite, and calcareous sandstone
Limestone and shale
Middle and Upper Cambrian
Lower Cambrian
Silver Peak group
CAMBRIAN
Sandstone and dolomite
PRE-CAMBRIAN(?)
Contact
Contact between intrusive rocks
Fault
Principal mines in the area
WHITE MOUNTAINS
INYO RANGE
SIERRA NEVADA
WHEELER CREST
ROUND VALLEY
TUNGSTEN HILLS
MT HUMPHREYS
COYOTE FLAT
MT DARWIN
MT POWELL
NORTH PALISADE
MIDDLE PALISADE
THE THUMB
BIRCH MTN
MT TINEMAHA
GOODALE MTN
CRATER MTN
POVERTY HILLS
RED MTN
WAUCOBA CANYON
ANDREWS MTN
WAUCOBA MTN
MT BAXTER
KEARSARGE PK
MT WILLIAMSON
MT WHITNEY
MT LANGLEY
NEW YORK BUTTE
ALABAMA HILLS
Coldwater Canyon
Silver Canyon
Laws
Bishop
Big Pine
Independence
Lone Pine
Keeler
Owens Lake
INDEX

DIVISION OF MINES
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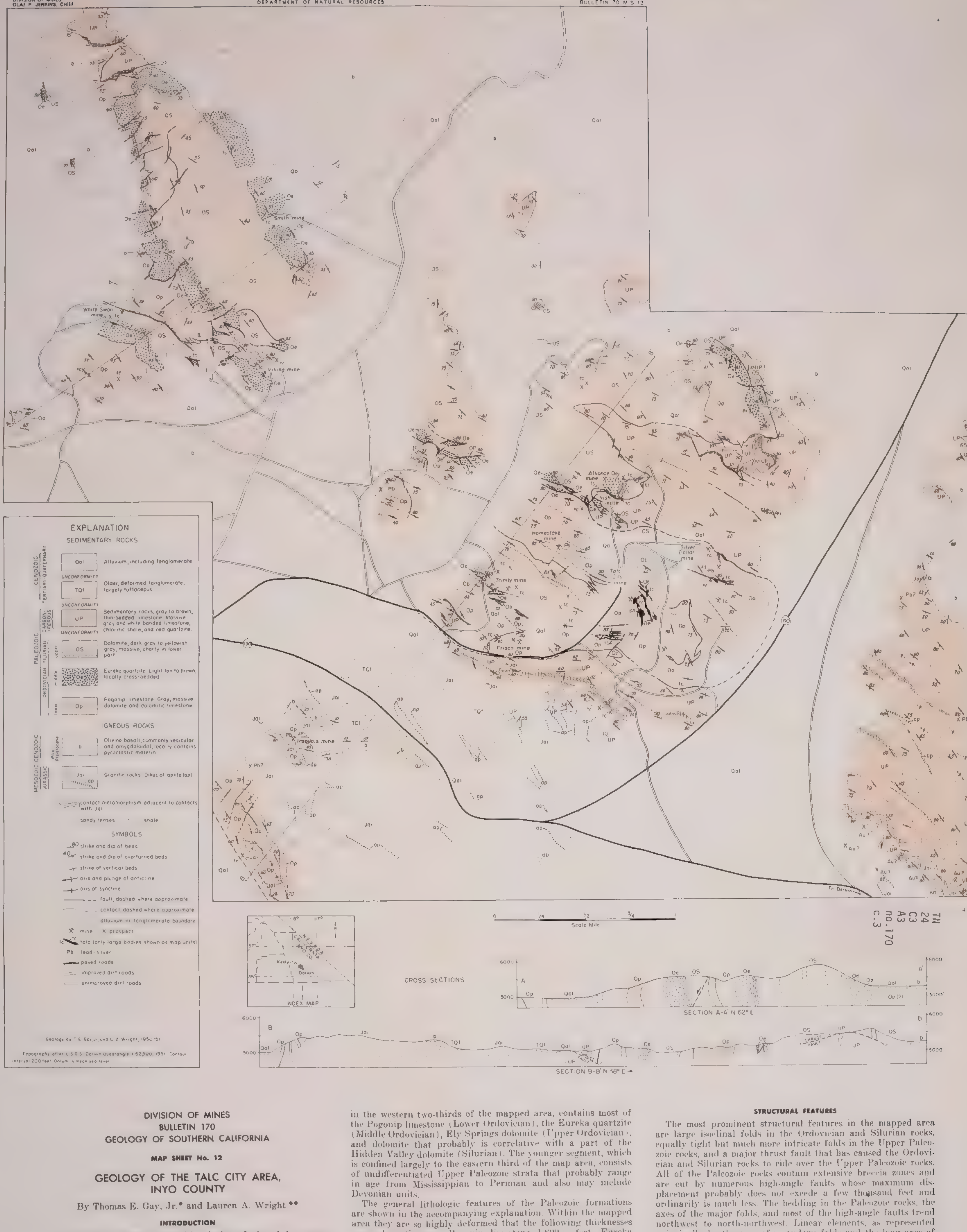
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 11

Cartography by E. T. McDermott

GEOLOGIC MAP OF THE
OWENS VALLEY REGION, CALIFORNIA


EXPLANATION
SEDIMENTARY ROCKS
CENOZOIC
TERTIARY-QUATERNARY
Qal Alluvium, including fanglomerate
UNCONFORMITY
TQf Older, deformed fanglomerate, largely tuffaceous
UNCONFORMITY
PALEOZOIC
CARBONIFEROUS
UP Sedimentary rocks, gray to brown, thin-bedded limestone. Massive gray and white banded limestone, chloritic shale, and red quartzite.
UNCONFORMITY
SILURIAN
upper
OS Dolomite, dark gray to yellowish gray, massive, cherty in lower part
ORDOVICIAN
middle
Oe Eureka quartzite. Light tan to brown, locally cross-bedded
lower
Op Pogonip limestone. Gray, massive dolomite and dolomitic limestone.
IGNEOUS ROCKS
MESOZOIC CENOZOIC
Plio-Pleistocene
b Olivine basalt, commonly vesicular and amygdaloidal, locally contains pyroclastic material
JURASSIC
Jgr ap Granitic rocks. Dikes of aplite (ap)
contact metamorphism adjacent to contacts with Jgr
sandy lenses
shale
SYMBOLS
80 strike and dip of beds
40 strike and dip of overturned beds
strike of vertical beds
axis and plunge of anticline
axis of syncline
fault, dashed where approximate
contact, dashed where approximate
alluvium or fanglomerate boundary
mine
prospect
tc talc (only large bodies shown as map units)
Pb lead-silver
paved roads
improved dirt roads
unimproved dirt roads
Geology by T. E. Gay, Jr., and L. A. Wright, 1950-51
Topography after U.S.G.S. Darwin Quadrangle 1:62,500, 1951. Contour interval 200 feet. Datum is mean sea level.
White Swan mine
Smith mine
Viking mine
Alliance Oe mine
Irish Lease
Homestake mine
Silver Dollar mine
Talc City mine
Trinity mine
Frisco mine
Iroquois mine
To Darwin
0 1/4 1/2 3/4 1
Scale Mile
INDEX MAP
Keeler
Darwin
INYO CO
NEVADA
CALIFORNIA
CROSS SECTIONS
SECTION A-A' N 62° E
SECTION B-B' N 38° E
6000
5000
A
A'
B
B'

TN
24
C3
A3
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c.3

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MAP SHEET No. 12

GEOLOGY OF THE TALC CITY AREA, INYO COUNTY

By Thomas E. Gay, Jr.* and Lauren A. Wright **

INTRODUCTION

The Talc City area, as defined by the boundaries of the accompanying map, embraces a group of northwest- to northeast-trending ridges at the southern end of the Inyo Mountains and within the Darwin quadrangle. These ridges, which are separated by alluviated valleys, are underlain mostly by structurally complex Paleozoic marine sedimentary rocks. These rocks form parts of a thick Paleozoic section that occurs extensively in the central part of the Inyo Mountains. The exposures of Paleozoic rocks in the Talc City area are separated from those to the north by a cover of late Tertiary or Quaternary basalt flows, the southern part of which extends into the mapped area. The Paleozoic rocks are bordered on the south and southwest by a large body of Mesozoic granitic rocks.

The area derives its name from the Talc City mine, which for many years was the nation's principal source of high-purity steatite talc, and which is still active. The area also contains numerous smaller talc mines and prospects, and the Silver Dollar lead-silver mine. The mapping was done primarily to record the geological setting of the talc deposits, which previously were studied in detail by Page (1951). Formational correlations were made with the helpful advice of C. W. Merriam, W. E. Hall, and E. M. MacKevett. The Paleozoic rocks closely resemble some of those in the Quartz Spring area of the Panamint Range, which have been described by McAllister (1952). A map and report covering the Darwin quadrangle currently are in preparation by Hall and MacKevett.

ROCK FORMATIONS

The Paleozoic rocks of the mapped area consist of two segments of the regional Paleozoic section. These are separated by a major thrust fault. The older segment, which is exposed mainly in the western two-thirds of the mapped area, contains most of the Pogonip limestone (Lower Ordovician), the Eureka quartzite (Middle Ordovician), Ely Springs dolomite (Upper Ordovician), and dolomite that probably is correlative with a part of the Hidden Valley dolomite (Silurian). The younger segment, which is confined largely to the eastern third of the map area, consists of undifferentiated Upper Paleozoic strata that probably range in age from Mississippian to Permian and also may include Devonian units.

The general lithologic features of the Paleozoic formations are shown in the accompanying explanation. Within the mapped area they are so highly deformed that the following thicknesses are only estimates: Pogonip limestone 1,800+ feet, Eureka quartzite 450± feet, Ely Springs dolomite 900± feet. Although the Upper Paleozoic strata are intensely folded and faulted and show a rather monotonous lithology, they appear to form a 1500- to 2000-foot segment of the Paleozoic section.

The most distinctive of the Paleozoic formations is the Eureka quartzite, which through the western part of the area maintains a uniform thickness and serves as an excellent marker. Toward the central part, however, the quartzite thins and is represented by numerous small and irregular masses whose origin has been puzzling (Page, 1951, p. 8). The uniform thickness of this quartzite in terranes of less structural complexity suggests that the extenuation is largely a deformational rather than a stratigraphic feature. Another excellent marker is a fossiliferous zone that exists 100 feet to 150 feet below the top of the Pogonip limestone and contains abundant remains of the gastropod *Maclurites*.

The granitic rock that underlies the southern part of the mapped area apparently is a part of the large body of Coso granodiorite recognized by Kelley (1938, p. 514) in the Darwin area. It shows sharp, intrusive contacts with the Paleozoic rocks and locally has produced zones of silication in the bordering carbonate strata. Acidic dikes cut the Paleozoic sedimentary rocks as well as the granitic rocks. At the Frisco mine, acidic dikes that cut dolomite of the Pogonip limestone have been altered to massive chlorite, whereas the bordering dolomite has been altered to steatite talc.

Late Tertiary or early Quaternary fanglomerate intermixed with pyroclastic material occurs locally beneath the olivine basalt flows. It shows little deformation, and is 200 feet or less in exposed thickness. Although the overlying basalt occurs mostly in flows, small plugs are common. Most of the flows are essentially horizontal, but they locally show dips of as much as 40 degrees.

STRUCTURAL FEATURES

The most prominent structural features in the mapped area are large isoclinal folds in the Ordovician and Silurian rocks, equally tight but much more intricate folds in the Upper Paleozoic rocks, and a major thrust fault that has caused the Ordovician and Silurian rocks to ride over the Upper Paleozoic rocks. All of the Paleozoic rocks contain extensive breccia zones and are cut by numerous high-angle faults whose maximum displacement probably does not exede a few thousand feet and ordinarily is much less. The bedding in the Paleozoic rocks, the axes of the major folds, and most of the high-angle faults trend northwest to north-northwest. Linear elements, as represented principally by the axes of secondary folds and the long axes of dolomite *boudinages* in Pogonip limestone, commonly plunge moderately to steeply southwest. The thrust fault has a very irregular trace, and the fault plane has the form of northwest-trending folds. These indicate post-thrust deformation concurrent with at least some of the folding of the Paleozoic rocks.

TALC DEPOSITS

The talc deposits within the mapped area are confined to the dolomitic rocks and to the associated quartzite and acidic intrusive rocks. The deposits are especially abundant at the contacts between the Eureka quartzite and the dolomites above and below it, but they also are widely distributed throughout the Ordovician and Silurian formations. Talc alteration was not observed in the Upper Paleozoic units. The talc bodies are lenticular to very irregular in shape, and range in long dimension from a few inches to several hundred feet. In general, the alteration appears to have been localized along zones of fracturing and shearing. Many of the talc bodies have border zones of porous calcareous rock that is an alteration of dolomite, which appears to have been the source of much or all of the additive magnesia. The restriction of the talc deposits to the dolomite-rich part rather than the limestone-rich part of the Paleozoic section also suggests a sedimentary origin for the magnesia.

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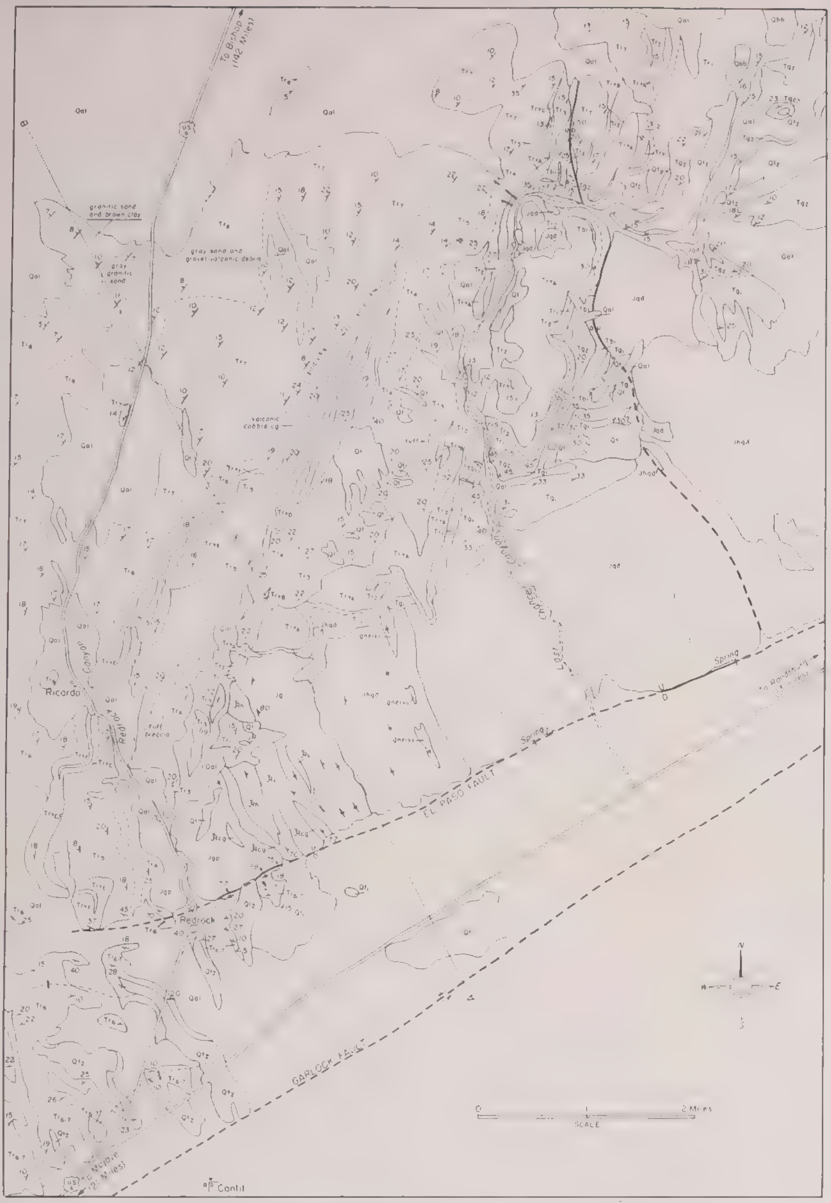
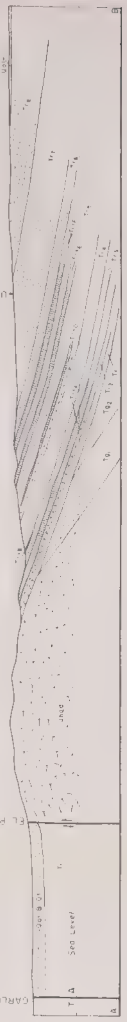
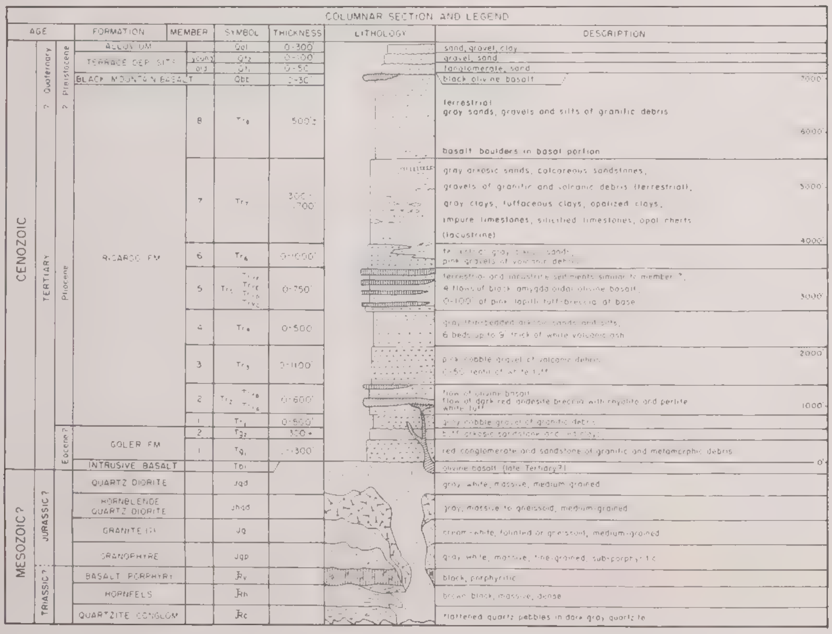
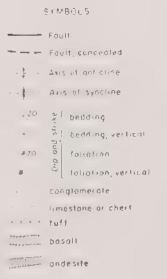






COLUMNAR SECTION AND LEGEND

AGE			FORMATION	MEMBER	SYMBOL	THICKNESS	LITHOLOGY	DESCRIPTION
CENOZOIC	? Quaternary	? Pleistocene	ALLUVIUM		Qal	0-300'		sand, gravel, clay
			TERRACE DEPOSITS	young	Qt_2	0-100'		gravel, sand
				old	Qt_1	0-50'		fanglomerate, sand
			BLACK MOUNTAIN BASALT		Qbt	0-30'		black olivine basalt
	TERTIARY	Pliocene	RICARDO FM	8	Tr_8	500'±		terrestrial gray sands, gravels and silts of granitic debris basalt boulders in basal portion
				7	Tr_7	300'-700'		gray arkosic sands, calcareous sandstones, gravels of granitic and volcanic debris (terrestrial), gray clays, tuffaceous clays, opalized clays, impure limestones, silicified limestones, opal cherts (lacustrine)
				6	Tr_6	0-1000'		terrestrial gray arkosic sands, pink gravels of volcanic debris
				5	Tr_5	0-750'		terrestrial and lacustrine sediments similar to member 7, 4 flows of black amygdaloidal olivine basalt, 0-100' of pink lapilli tuff-breccia at base
				4	Tr_4	0-500'		gray thin-bedded arkosic sands and silts, 6 beds up to 9' thick of white volcanic ash
				3	Tr_3	0-1100'		pink cobble gravel of volcanic debris, 0-50' lentil of white tuff
				2	Tr_2	0-600'		flow of olivine basalt flow of dark red andesite breccia with rhyolite and perlite white tuff
				1	Tr_1	0-500'		gray cobble gravel of granitic debris
		Eocene ?	GOLER FM	2	Tg_2	300'+		buff arkosic sandstone and red clays
				1	Tg_1	0-300'		red conglomerate and sandstone of granitic and metamorphic debris
			INTRUSIVE BASALT		Tbi			olivine basalt (late Tertiary?)
MESOZOIC?	JURASSIC ?		QUARTZ DIORITE		Jqd			gray-white, massive, medium grained
			HORNBLENDE QUARTZ DIORITE		Jhqd			gray, massive to gneissoid, medium-grained
			GRANITE (?)		Jg			cream-white, foliated or gneissoid, medium-grained
			GRANOPHYRE		Jgp			gray-white, massive, fine-grained, subporphyritic
	TRIASSIC ?		BASALT PORPHYRY		℞v			black, porphyritic
			HORNFELS		℞h			brown-black, massive, dense
			QUARTZITE CONGLOM		℞c			flattened quartz pebbles in dark gray quartzite



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MAP SHEET NO. 13

GEOLOGY OF THE REDROCK CANYON-LAST CHANCE CANYON AREA, KERN COUNTY

By T. W. Dibblee, Jr.*

INTRODUCTION

The Redrock Canyon-Last Chance Canyon area is about 25 miles northeast of Mojave, and is included within the 15-minute Saltdale quadrangle (Dibblee, 1953). Redrock Canyon, which drains southward into the Mojave Desert (here about 2,000 feet in altitude), lies between the southern Sierra Nevada on the west and the El Paso Range extending northeast. Four miles east of Redrock Canyon is Last Chance Canyon, which drains the northwest slope of the El Paso Range and thence turns southward through an antecedent gorge across this range into the Mojave Desert. Both canyons cut through a series of tilted Tertiary sedimentary and volcanic rocks; the lava flows appear as strike ridges, and the softer sediments have been eroded into the scenic badlands for which these canyons are famous.

STRATIGRAPHY

Older Rocks. A basement complex in this area is composed of plutonic rocks intrusive into an older series of metamorphic rocks. The latter includes quartzite conglomerate, hornfels, and basalt porphyry, and trends northwest. The age of these rocks is not known.

The plutonic rocks probably are parts of the Sierra Nevada batholith of supposed Jurassic age. They consist of massive quartz diorite and hornblende quartz diorite exposed in Last Chance Canyon. Farther west are exposures of hornblende quartz diorite and granite(?) with a gneissoid foliation that is either a flow structure or a relict structure. Inclusions of banded gneiss also are present. A fine-grained rhyolite granophyre at Redrock Canyon is unlike any other rock in this region, and apparently is intrusive into the quartzite conglomerate.

The Goler formation, a series of terrestrial sediments, is exposed in Last Chance Canyon where it rests on quartz diorite. The basal conglomerate (member 1) grades from coarse boulder-cobble conglomerate at the base to maroon-red pebbly arkosic sandstone at the top. This unit is overlain by the basal portion of the upper Goler (member 2), which consists of red clays and buff arkosic sandstones. The Goler formation has not yielded a diagnostic vertebrate fauna, but fossil leaves of probable Eocene age have been found in a basal coal bed east of Last Chance Canyon (Axelrod, 1948).

Ricardo Formation. The Ricardo formation, named by Merriam (1914), is a series of terrestrial and lacustrine sediments, tuff, and lava flows of Pliocene age. It attains a maximum thickness of nearly 7,000 feet in Redrock and Last Chance Canyons, where it rests unconformably on the Goler formation and the basement complex. The formation has been divided into eight members, as shown on the accompanying map and sections. These can be grouped into two divisions: the lower Ricardo (member 1 through 5) is composed of a basal arkosic conglomerate (member 1), followed upward by tuff, lava, conglomerate with volcanic debris, sandstone, and lacustrine beds (members 2 through 5); the upper Ricardo (members 6 through 8) is composed of lacustrine sediments and terrestrial sediments with volcanic and granitic debris.

The Ricardo formation is coarsest west of Redrock Canyon, and the lower three members buttress out in that canyon. The formation reaches its maximum development in Last Chance Canyon, where fine-grained lacustrine sediments constitute a large part of the section, and it thins rapidly to the northeast. The flows of basaltic lava are believed to have extended from the basalt dikes that are exposed in Last Chance Canyon, and the masses of andesite lava, which contains some rhyolite and perlite, may have been extruded on the east side of this canyon. A large vertebrate fauna has been obtained from the upper Ricardo formation in Redrock Canyon by Merriam (1919), and indicates a lower Pliocene age.

Terrace Deposits. Terrace gravels occur on at least two levels in Redrock and upper Last Chance Canyons. These are remnants of an older alluvium that has been elevated and largely eroded away.

STRUCTURE

Redrock and Last Chance Washes follow antecedent canyons that were cut across the southwest end of the El Paso Range when it was elevated as a block and tilted northwestward. Much of the uplift took place on a major fault, the El Paso fault, which extends along the southeastern base of the range. The resistant rocks of the basement complex form the hard core of the tilted block, and the overlying Tertiary strata dip uniformly northwestward away from the core. The mountain block was elevated in two stages, one after deposition of the Goler formation and the other after deposition of the Ricardo formation, as indicated by the angular unconformity between these two units.

The El Paso fault is well exposed on the east side of Redrock Canyon, where it separates the basement complex of the elevated block on the north and soft sediments of the Ricardo formation on the south. The fault here dips 75° to 90° north, and is marked by several feet of pulverized granophyre. The throw amounts to about 3,000 feet at this point, and it decreases westward and increases eastward. This fault is a branch of the Garlock fault, which lies concealed beneath the valley alluvium about two miles to the south. Movement on the Garlock fault has been mainly horizontal, with the northwest block displaced relatively southwest (left lateral) for a total distance of 6 miles or more. Between the Garlock and the El Paso faults the Ricardo formation has been compressed into an anticline and a syncline whose axes trend north of east.

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GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 14

GEOLOGY OF THE ROSAMOND HILLS, KERN COUNTY *

By James A. Noble †

Introduction. The Rosamond Hills form a topographic unit about 20 miles long and 10 miles wide in the southern part of Kern County. Rosamond on the south, Mojave on the north, and Willow Springs on the west mark the approximate limits of the hills; the eastern boundary is somewhat indefinite. The town of Rosamond is on U. S. Highway 6, approximately 85 miles from Los Angeles. The hills are of interest geologically because they expose the bedrock in Antelope Valley, a triangular westward extension of the Mojave Desert enclosed by two of the large faults of southern California, the San Andreas and the Garlock. The ore deposits in the area are shallow-seated or volcanic deposits.

The following brief description of the geology of the Rosamond Hills is essentially a preliminary report on a study not yet completed. The extrusive and intrusive rocks of the southwestern portion of the hills have been studied in detail, but investigations of the important Soledad Mountain area are still in progress; hence the following generalizations regarding igneous intrusion and ore mineralization may not fully apply to Soledad Mountain.

Topography. The topography of the Rosamond Hills warrants detailed study because here, as in so much of the arid Southwest and particularly in southern California, there is a strong temptation to use topography to solve structural problems. The hills, as viewed northward from the floor of Antelope Valley, appear to present a subdued but well-defined east-west bounding scarp. As seen on detailed topographic maps and air photographs, however, the hills actually comprise two low lines of ridges that trend west-northwest and are partly encircled by some conical or oval hills. Closer study on the ground reveals that one line of ridges is formed by zones of pegmatite and aplite that trend west-northwest in an otherwise non-resistant pre-Tertiary quartz monzonite; the other line of ridges is a dissected cuesta developed on Miocene (?) tuffs and agglomerates that strike west-northwest, and the scattered conical and oval hills mark the outlines of swarms of small stocks and dikes and perhaps explosive vents of rocks of essentially rhyolitic composition.

A minor topographic feature is a mature erosion surface that is preserved on the tops of the two largest hills of intrusive rock, Soledad Mountain and Middle Buttes. This surface, with its fairly deep mantle of reddish clay, is in striking contrast to the steep sides of the hills. Another minor topographic feature, also developed on the hills of intrusive rocks, reflects a heavy draping mantle of indurated mud-flows which, on Willow Springs Mountain and probably on the other hills as well, once made a continuous sheet around the lower half of the mountain with a lobate fringe merging and interfingering with gravels derived from the Tehachapi Mountains to the north. Subsequent dissections of these mud-flows has yielded material that has been redeposited in symmetrical fans to give the round or oval forms like that so strikingly shown by Willow Springs Mountain.

Rocks. The oldest rock in the area is a medium-grained quartz monzonite. It occupies the northeast part of the district and also crops out around the hills of younger intrusive rocks. Small zones of aplite and swarms of small pegmatite dikes are common, and, being more resistant to erosion, these rocks break the monotony of the smooth erosion surfaces of the weathered quartz monzonite.

Strata of the Rosamond series rest on the quartz monzonite on what seems to have been an erosion surface of low relief. This series has been studied in detail by W. B. Roberts (1951), the results of whose work have been utilized on the accompanying map and in formulating the following generalizations. The basal unit is generally a white tuffaceous agglomerate or conglomerate, with rounded boulders, cobbles, and pebbles mainly of rhyolitic rocks and less abundantly of quartz monzonite. This white member ranges in thickness from a few feet up to 300 feet, but is notably thinner to the west. In many places it is overlain by a pinkish lapilli tuff that is as much as 120 feet in thickness. The next member generally is what Roberts called green volcanic conglomerate—a heterogeneous member mainly of clastic origin but everywhere with some volcanic matrix. It ranges from 700 to 800 feet in thickness, and is the thickest member of the section. Above this unit in the west end of the district is a brown fanglomerate as much as 500 feet thick. Some welded tuff in this same part of the district may intervene below the fanglomerate, or may have been dropped into the section by faulting. In the east end of the district either the brown fanglomerate cuts down stratigraphically to rest upon the basal white agglomerate, or an additional unit of brown fanglomerate occurs there.

Intrusive into the Rosamond series are many small stocks and dikes of essentially rhyolitic composition. Many of the rhyolites, though clearly intrusive in form, show a degree of well-defined flow banding usually found only in surface flows, whereas others are dense and structureless. Most of the rhyolites contain sparse phenocrysts of feldspar and some quartz and biotite, but a few of them have abundant phenocrysts, generally small but locally as much as 4 mm in diameter.

An intrusive rock, sufficiently different from the rhyolites in appearance in the field and in hand specimen to justify separation on large-scale maps, is a feldspar porphyry with dark gray or reddish purple groundmass. This rock does not show good flow banding or other internal structures. Its age relation to the rhyolites is not well established, because in some places, as on Tropico Hill, it is younger than all the rhyolites, and in others, as on Willow Springs Mountain, it both cuts and is cut by rhyolites.

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MAP SHEET 14

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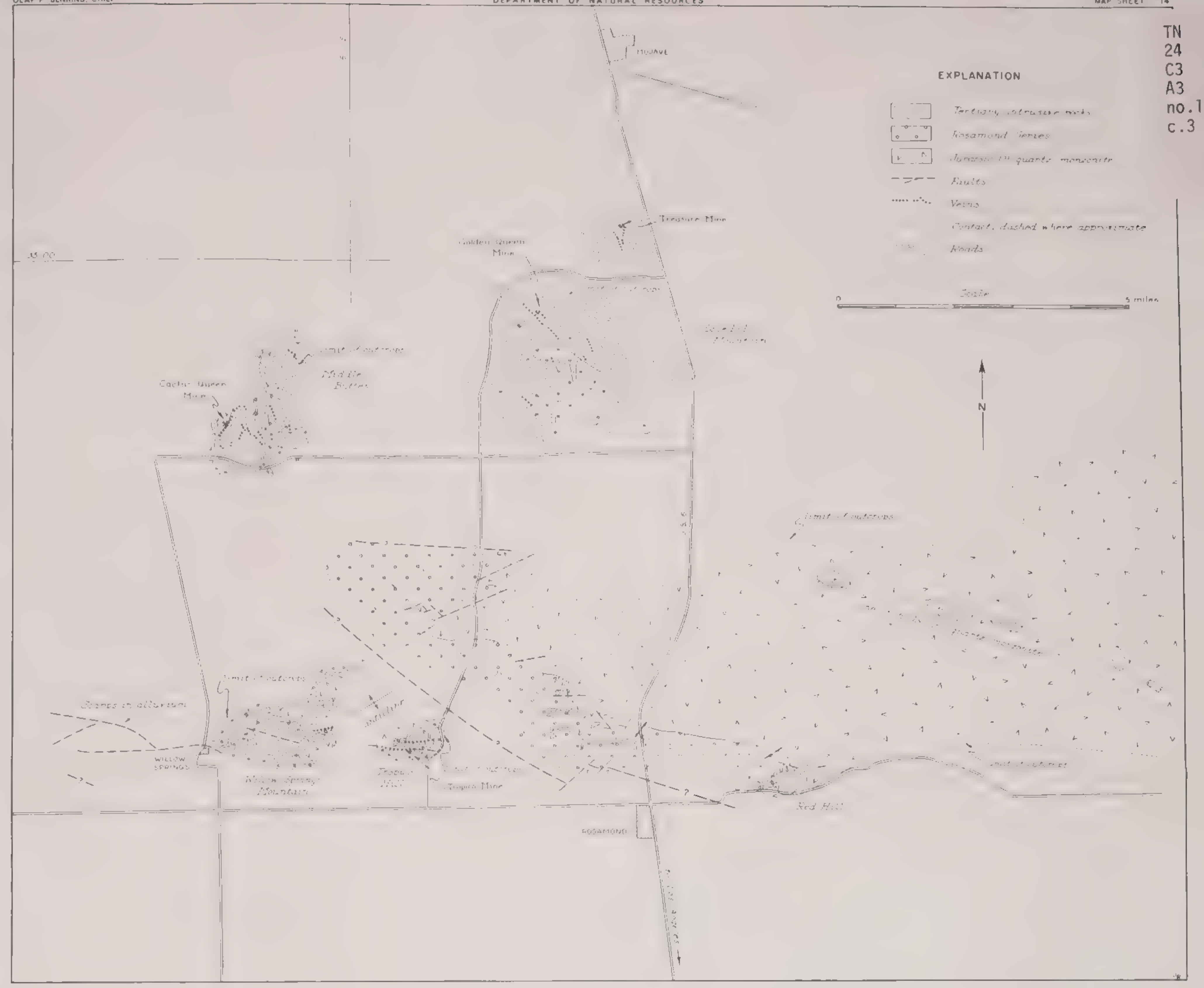

Another rock, mapped as intrusive breccia, may be in part extrusive. In a typical exposure, it is made up of angular, nearly rectangular fragments of banded rhyolite, from 3 inches to a foot on an edge, in a matrix of rhyolite fragments. In a few places a crude layering strongly suggests that at least parts of this rock were surface accumulations, but in most places the shapes of the bodies are those of an intrusive, not an extrusive, rock. The most reasonable genetic explanation seems to be that the breccias formed when rhyolite magma rose to subsurface levels where the external pressure was insufficient to prevent an explosion of the dissolved gases, the resulting angular debris collecting in a volcanic neck or on the surface, so that some bodies are intrusive but others are extrusive and grade into bedded agglomerates. On Tropico Hill the intrusive breccias are the oldest intrusive rock, but on Willow Springs Mountain some breccias seem to cut some rhyolite and are cut by other rhyolites.

Earlier descriptions of the Rosamond series in this, its type locality, include mention of rhyolite flows, but Roberts found only a few flows of andesite or basalt, and the author has found only one flow of glassy rhyolite of small areal extent.

Structure. In its main area of exposure, the Rosamond series crops out as a monoclinal sequence that strikes west-northwest and dips south-southwest at about 20 degrees. Southwest of this area, the series forms an anticline with an axis trending east-northeast. There certainly is not room enough between these two outcrop areas to make an adjustment between the attitudes of their respective strata by folding, and the best interpretation, as suggested by Roberts (1951), calls for a fault with a west-northwest strike and with considerable displacement. This displacement, moreover, would require, in accord with present evidence, a strike-slip movement of at least several miles.

Smaller faults are common throughout the Rosamond Hills. In his mapping of the Rosamond series, Roberts found many breaks of widely divergent trends, a common direction being east-west. One fault with east-northeast trend was found to have a considerable displacement. In the intrusive areas of Tropico Hill, Willow Springs Mountain, and Middle Buttes, faults that strike west-northwest probably are most numerous, but faults with many other trends have been noted.

Ore Deposits. The ore deposits of the Rosamond Hills are predominantly gold deposits of the type variously known as epithermal, volcanic, or bonanza. Four of the intrusive centers, namely Soledad Mountain, Middle Buttes, Tropico Hill, and Willow Springs Mountain, show a close space association between the centers of intrusion and the areas of mineralization, but neither of the other two centers of intrusion, Red Hill and the unnamed area 2 miles northwest of the town of Rosamond, nor any other areas away from centers of igneous intrusion, have yielded commercial ore.

At each of the mineralized centers, the ore deposits show structural control by fracturing, which is well defined for the particular center but distinct from that of other centers. The exception to this generalization is that the structural control is the same on Tropico Hill as on Willow Springs Mountain, a mile or two away. On this pair of hills the veins trend west to west-northwest and dip south at about 60°. In the Tropico mine the main vein shows ore on the 750-foot level, but other veins have been explored to depths of only about 200 feet. On Middle Buttes some strong veins with northeast strikes and southeast dips of 35° have been mined to depths of 800 feet. In this area there are in addition some less clearly defined zones with northwest trends that also have been mined. On Soledad Mountain, northwest trends are the rule and there are many veins, with mining or development to depths of about 500 feet in places. In each district the veins cut all the igneous rocks in fairly straight lines, and they occupy post-intrusion faults with displacements that in places are measured in hundreds of feet. There is a little post-ore faulting, generally with minor displacement.

Quartz is the most abundant vein mineral, and sericitization is common as a wall-rock alteration. Alunitization is locally very conspicuous. Native gold, generally in sizes barely large enough for panning, is the only ore mineral in some places, as at the Tropico mine. In other areas sulfides are visible and form as much as 1 percent of the ore, but their grain size is very fine, and except for pyrite they can be identified only under the microscope. The northeast-trending veins of the Middle Buttes contain, in addition to quartz, adularia, pyrite, free gold, and small amounts of marcasite, chalcopyrite, sphalerite, galena, tetrahedrite, ruby silvers, argentite, and cinnabar. On the other hand, the northwest-trending zones of alunitization in rhyolite contain only free gold, and have little silver. All the veins show clear evidence of successive shattering and recementation of the vein quartz during the process of mineralization, and the valuable constituents were deposited late in the sequence.

The gold veins of the Rosamond Hills are representative of a type of mineralization that is fairly widely distributed across the width of the Mojave Desert region, and continues eastward across Nevada (Ferguson, 1944). It is a type sufficiently distinct to call for a separate place in most classifications of ore deposits, where veins of this type are termed epithermal by Lindgren (1933, pp. 444-513) and sub-volcanic by Schneiderhohn (1941, pp. 377-387). They are referred to specifically by Schmitt (1950, p. 213) in a recent discussion of the so-called "epithermal" gold deposits.

A mineralization in this area to which attention only recently has been directed is that of uranium. Near Willow Springs Mountain a small amount of prospecting has disclosed mineralization in altered rhyolite, with samples containing 0.1 to 0.2 percent of U_3O_8. The radioactivity and colors resemble carnotite, but mineralogic determinations have not been made. About 3 miles to the northeast, a similar mineralization is scattered along bedding planes in bleached tuff, and in this area may be of somewhat better grade.

Problems. Problems of southern California geology on which the Rosamond Hills area may throw some light include the origin of the Rosamond series and its position in the stratigraphic column, as well as the relation of the faulting to the San Andreas and Garlock faults. The fact that the intrusive rhyolites everywhere cut the pyroclastic rocks of the Rosamond series at first glance seems to call for a source of the Rosamond outside the area, but the presence of the intrusive rhyolite breccias may hold the key to the origin of the pyroclastic material. These breccias clearly intrude the quartz monzonite and in places cut the Rosamond strata, but in other places they cannot be clearly separated from the Rosamond agglomerates and may in fact grade into these agglomerates. The breccias therefore may gradually change upward from intrusive to extrusive and outward from breccias to agglomerates; they may mark the sites of explosive vents that furnished the material for the igneous constituents of the Rosamond series. The crude bedding of some of the very coarse breccias of Middle Buttes could have formed in a volcanic neck.

Nothing can be added at this time to the discussion of the age of the Rosamond series beyond that already outlined by Simpson (1934, pp. 400-401). The suggestion of a middle Miocene age should be considered as wholly speculative until more evidence is disclosed.

The fault pattern of the Rosamond Hills, with strong faults of (probably) strike-slip displacement in directions west-northwest and east-northeast, is similar to the pattern of the San Andreas and Garlock faults, but it would be surprising if such were not the case, in view of the location of the area between these large faults. One looks in vain, however, for north-south tensional features to support a hypothesis of a north-south compression as a cause of the two directions of shearing.

A minor structural problem is whether or not an east-west fault should be shown as a boundary fault along the south side of the Rosamond Hills. Such a fault, known either as the Willow Springs fault or the Rosamond fault, has been included on previous geologic maps. Small scarps in the alluvium west of Willow Springs, with displacements of as much as 25 feet, are shown on the accompanying map. These trend east in general, but are somewhat arcuate, and indeed they curve rather sharply and die out as they approach the areas of rock outcrop just to the east. This failure of the scarps in gravel to cross onto bedrock areas raises the question of whether such scarps actually represent equivalent displacements in the underlying bedrock, here or in other gravel-filled basins in southern California. If the four centers of igneous intrusion, from Red Hill on the east to Willow Springs Mountain on the west, are localized on an east-west fault in the quartz monzonite basement, there is no other evidence for such a fault; moreover, it would have to be considerably older than the displacements in the gravels.

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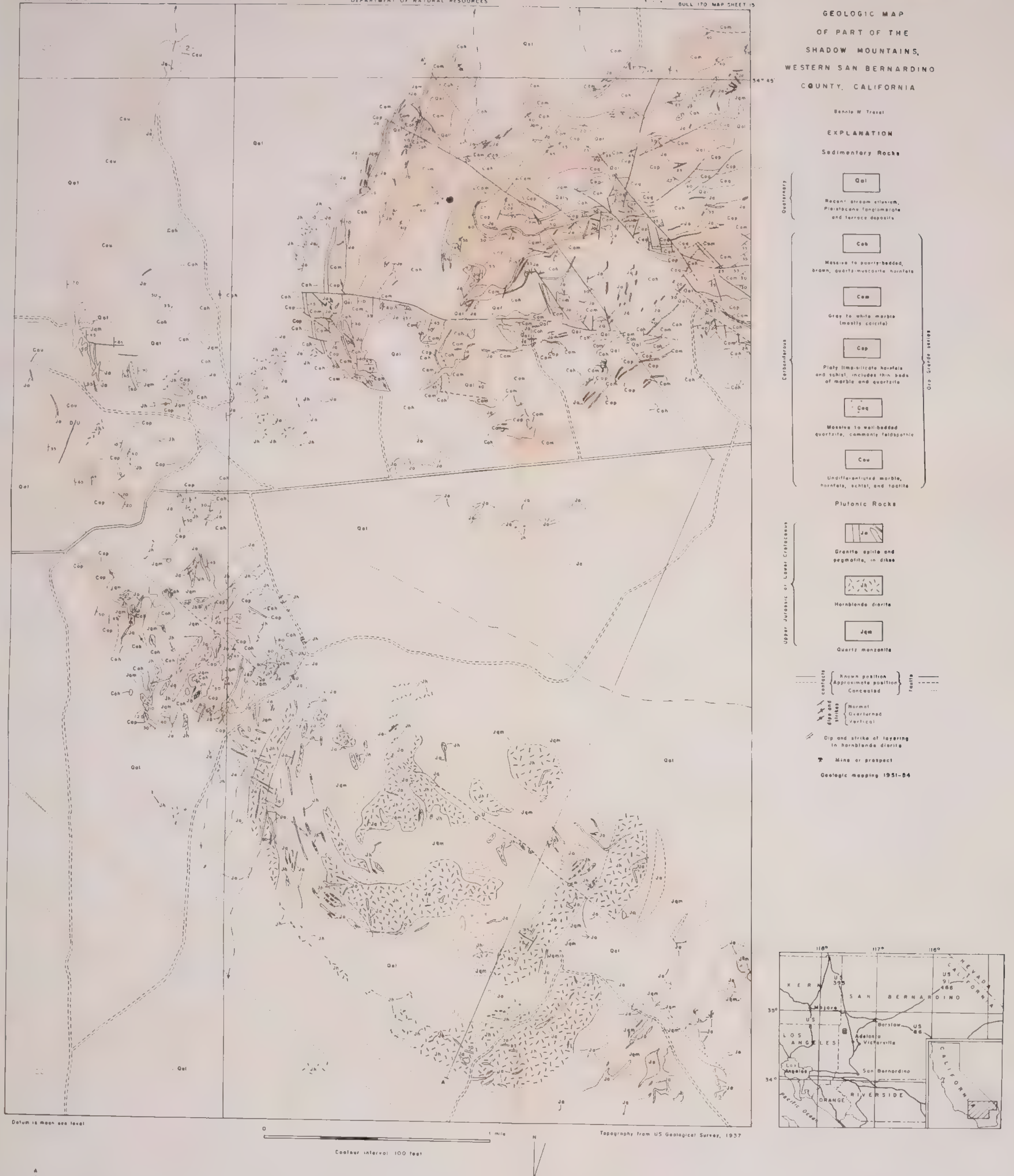
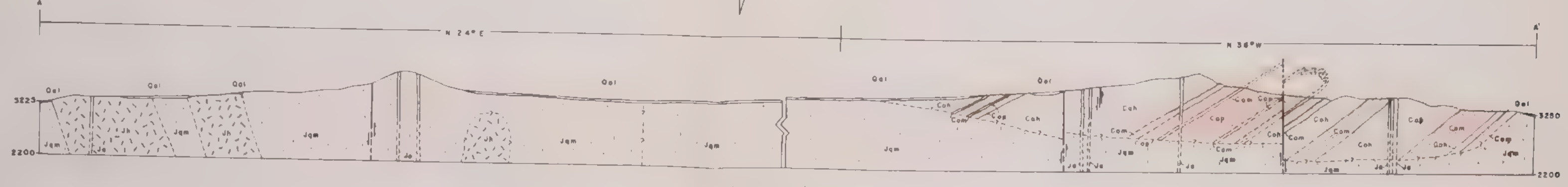
BULL 170 MAP SHEET 15





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DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 15

GEOLOGY OF A PART OF THE SHADOW MOUNTAINS WESTERN SAN BERNARDINO COUNTY

By Bennie W. Troxel *

INTRODUCTION

The Shadow Mountains, a group of low hills in western San Bernardino County, are underlain chiefly by a series of Paleozoic metasedimentary rocks and various intrusive rocks of probable late Jurassic to early Cretaceous age. The metasedimentary rocks form the main part of the hills in the north half of the area mapped. They exist as roof pendants in the quartz monzonite, which underlies the flanks of the hills and generally is concealed beneath a thin cover of Quaternary alluvium. This alluvial capping lies upon pediment surfaces of low relief that slope outward from the flanks of the more resistant rocks.

The hills contain commercial deposits of scheelite and of white carbonate rocks that are crushed and marketed for use as roofing granules. No published geologic maps of the Shadow Mountains exist, but similar or identical formations have been mapped and described in nearby areas (Hershey, 1902; Miller, 1944; Bowen, 1954).

ROCK UNITS

Metasedimentary Rocks. Marine metasedimentary rocks are exposed in the northern half of the area mapped. They consist mainly of unfossiliferous massive crystalline carbonate rocks (chiefly limestone), massive quartz-muscovite hornfels, and platy lime-silicate hornfels. Quartz-biotite schist, chert, and quartzite form a minor part of the series. Deformation has caused such extreme thickening and thinning of beds that an accurate measurement of the section is not practical. These rocks resemble strata of the Oro Grande (Carboniferous) series (Bowen, 1954) exposed in nearby areas to the east; fossils have been obtained from the lower part of the series.

These metamorphic rocks formerly existed as an apparently conformable series of alternating mudstone, limestone, sandy limestone, sandstone, and shale. It is estimated that they are between 3,500 and 5,000 feet thick in the area mapped. Schist and quartzite are the oldest strata exposed. They are overlain by platy lime-silicate hornfels and carbonate rocks. The upper one-half to two-thirds of the section is composed of alternating carbonate rocks and quartz-muscovite hornfels in nearly equal proportions. Metamorphism is principally dynamothermal, but in addition some rocks have been subjected to contact metamorphism. These latter rocks are composed principally of coarsely crystalline silicate minerals, most commonly wollastonite, calcite, garnet, idocrase, and epidote.

Intrusive Rocks. The intrusive rocks exposed in the Shadow Mountains are mostly biotite quartz monzonite and hornblende diorite. Quartz monzonite underlies most of the mountains, as well as the major part of the western Mojave Desert. It erodes easily and in general is poorly exposed. In the western part of the area mapped the intrusive contacts between the quartz monzonite and the metsedimentary rocks are sharp. Xenoliths of metasedimentary rocks in the quartz monzonite generally are less than 2 feet in diameter.

The hornblende diorite occurs principally as arcuate bodies which are as much as 900 feet thick. These appear to be dikes that intrude the quartz monzonite. It occurs also as thin dikes intrusive into metasedimentary rocks.

Granite aplite and pegmatite, in dikes and sills as much as 10 feet thick, are common throughout the Shadow Mountains.

Quaternary Rocks. The Quaternary rocks consist of a thin series of dissected older alluvial fanglomerate and terrace deposits, and alluvium of the present stream channels. In most places the fanglomerate probably does not exceed 20 feet in thickness.

STRUCTURAL FEATURES

An east-trending isoclinal anticline that is overturned to the north is the principal structural feature of the Paleozoic rocks. The anticline plunges gently westward, and its western tip is bent southward. Strong lineation plunges about 30° south at nearly every point where it was observed. Minor folds are a few inches to a few feet in average width. The south trend and plunge of the linear features coincide with the general structural grain of the western Mojave Desert. The east-trending fold probably developed in early Mesozoic time. This is based on the assumptions (1) that the metasedimentary rocks are Upper Paleozoic in age, and (2) that the aplite dikes, which cut the fold and are not markedly deformed, are of Mesozoic age.

The arcuate bodies of hornblende diorite form a discontinuous circular structure, apparently a ring dike, that is about 2 miles in diameter. Some of the hornblende diorite exhibits planar structures or layers parallel to the walls of the bodies. Some of the layering is caused by alternation of mafic and felsic minerals, and some is caused by differences in grain size. The dip of the layers ranges from vertical to 70° toward the center of the ring dike. A small swarm of vertical aplite dikes is intrusive into the hornblende diorite on the west side of the ring dike.

Three of several possible explanations for the formation of the circular structure are: (1) it is a ring dike composed of hornblende diorite intrusive into quartz monzonite, (2) it is a relict structure encompassing an older granitic igneous mass and intruded by quartz monzonite, (3) it is a feature of granitization. Further study of the structure is planned.

At least four northwest-trending faults traverse the mapped area. The component of apparent horizontal movement is small, and it appears to be of both right- and left-lateral displacement. Vertical displacement along at least two of the faults may be measured in hundreds of feet. The principal movement has probably been post-Cretaceous and pre-Quaternary.

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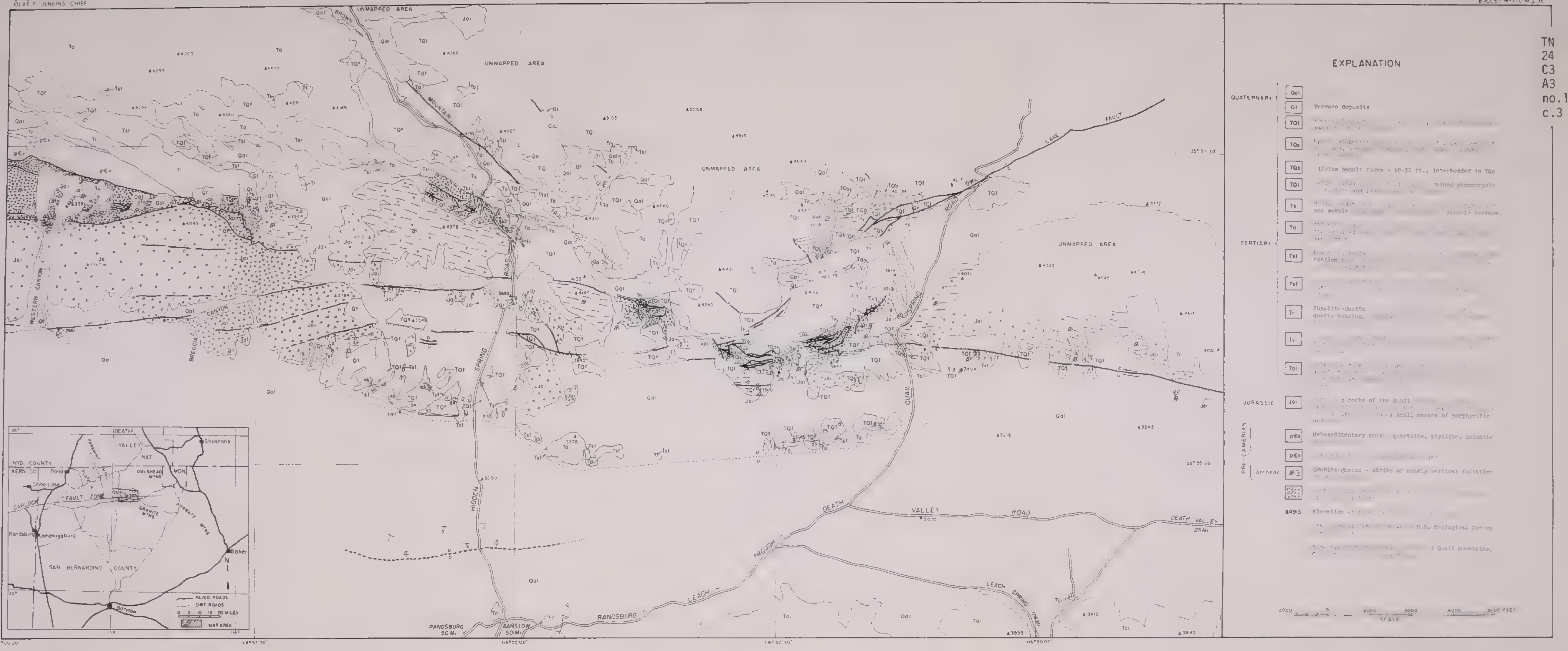

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 16

GEOLOGY OF THE QUAIL MOUNTAINS, SAN BERNARDINO COUNTY *

By William R. Muehlberger†

The Quail Mountains, in northern San Bernadino County, are about 20 miles southwest of Death Valley. They can be reached over unimproved desert roads from Death Valley, Barstow, or Randsburg. Most of the area shown on the accompanying map is within the limits of the reactivated Camp Irwin, and at present (1954) is closed to public entry.

Rock Units and Suggested Correlations. Acidic intrusive rocks of Archean, Jurassic, and early Tertiary age form the bulk of the rocks exposed on the southern flank of the Quail Mountains and on the northern flank of the Granite Mountains to the south. Pre-Jurassic sedimentary and volcanic rocks crop out locally near the western margin of the map area. An Upper Tertiary-Quaternary sequence of rhyolite, andesite, latite, basalt, and interbedded tuffs and sediments unconformably overlies the older crystalline rocks.

The correlations tentatively suggested in the following paragraphs are based on lithologic similarity and position in the stratigraphic sequence, and at present are not supported by fossil evidence or by determinations of absolute age.

The granite-gneiss of the map area is similar in mineralogy and structure to the gneiss of Archean age in the Ivanpah quadrangle to the east (Hewett, 1954).

In the northwest part of the map area is a wedge of sedimentary and volcanic rocks that are designated on the map as pJs and pJv, respectively. The age of these rocks is unknown, but the presence of quartzites, dolomites, and argillites with a thick sequence of volcanic rocks suggests that they may be Triassic. On the other hand, they may represent an eastward extension of the Paleozoic section that is exposed in the Slate Range immediately to the west.

The Jurassic intrusives of the region to the west (Jenkins, 1938) are parts of a belt that continues into the Quail Mountains. The intrusives of the Granite Mountains, on the other hand, are tentatively correlated with the early Tertiary (Laramide) intrusives of the Ivanpah quadrangle (Hewett, 1954) to the east, mainly on the basis of megascopic similarities.

No sequence of rocks in the Mojave Desert-Death Valley region is directly comparable to the late (?) Tertiary-Quaternary rocks of the map area. Thus far no fossils have been found in these rocks, and hence assignment of definite ages to the various map units in this part of the section is not feasible.

The widespread Red Mountain andesite of the Randsburg quadrangle (Hulin, 1925) to the west is late Miocene or early Pliocene in age, and the andesite (T_a) of the map area may well be correlative with this unit. Furthermore, underlying sequences of tuffs and agglomerates (T_{sl}) are present in both areas.

Underlying the Red Mountain andesite in the Randsburg quadrangle (Hulin, 1925) is the Rosamond series of mid-Miocene age, which contains rhyolite flows and coarsely clastic sedimentary material. The rhyolite (T_r) and associated quartz-free volcanic rocks (T_v) of the map area may correspond to this portion of the Rosamond series.

The youngest major volcanic activity in the Quail Mountains resulted in the outpouring of the latite flows that cap much of the central part of the range. Hewett (1954) describes a similar sequence from the Ivanpah quadrangle, and states that it is late Tertiary in age. The uppermost flows are interbedded with the overlying Funeral fanglomerate in the map area. Noble (1941) believes that this fanglomerate is Pliocene in age, although parts of it may be early Pleistocene. The association of the uppermost latite flows with basalt flows that typically are present in the Funeral fanglomerate suggests that the latite may be in part of early Pleistocene age, although the bulk of it probably is Pliocene.

Garlock Fault Zone. The Garlock fault zone trends eastward along the southern flank of the Quail Mountains. It is more than one and a half miles wide, and consists of several distinct breaks with associated Recent scarps, as well as belts of crushed rocks that show no evidence of Recent faulting.

Offset streams within the map area suggest left-lateral displacements with a maximum Recent slip of about 2,000 feet. Near the Hidden Springs road, the steeply dipping contact between the Archean granite-gneiss and the overlying rhyolite apparently has been offset about a mile along the fault. Slices of some of the distinctive horizons of the sedimentary sections are present in the fault zone a mile to a mile and a half beyond the easternmost exposures of these rocks in the Quail Mountains. All evidences of lateral displacements are consistent, in that they indicate relative eastward movement along the south side of the fault.

Dip-slip offsets show that rocks on the north side of the fault have moved upward relative to those on the south side. Offsetting of mature erosion surfaces indicates 50 to 200 feet of vertical displacements. Scarplets in the alluvium have maximum heights of 40 feet. Some of them face the range, and mark the edges of minor grabens along the base of the range.

Zones of profound crushing are well exposed in both Breccia and Western Canyons, where pre-Tertiary igneous rocks and overlying Tertiary rhyolite have been reduced to angular fragments, 1 inch to 2 inches in diameter, that are set in a matrix of pulverized material. The crushing has not been uniform, and several slices and slivers of only partially shattered rock are present.

The Funeral fanglomerate west of the Brown Mountain fault contains large boulders of platy or schistose rhyolite. It is possible that this planar structure is a result of primary flowage, but the rhyolite, where exposed in place, shows little of this structure except within the crushed zones noted above. It seems reasonable to assume that the planar structure represents an early stage in the crushing of the rhyolite, and hence that movement along the Garlock fault in this area began sometime after extravasation of the rhyolite and prior to deposition of the Funeral fanglomerate. Also, judging from the slight amount of shearing in the rhyolite that forms boulders in the Funeral fanglomerate, relative to that in the rhyolite of the crushed zones, most of the shearing must have occurred subsequent to deposition of the Funeral fanglomerate. This suggestive evidence of late Tertiary inception of movement along the Garlock fault zone does not exclude the possibility of earlier movements elsewhere in the zone.

Only contacts between distinguishable rock types in the crushed zones are shown on the map, and no attempt has been made to delineate individual fault planes within these zones. Total displacement on the Garlock fault in this area is not known, but the available evidence suggests at least 1 mile to 2 miles of left-lateral movement with a north-side-up component of dip slip totaling a few thousand feet.

Brown Mountain Fault. The Brown Mountain fault trends northwest across the central Quail Mountains to the foot of Brown Mountain, 3 miles north of the map area. It is parallel with, and may be a branch of, the Panamint fault, which bounds the Panamint Range on the west side. At its southeast end it joins the Garlock fault. In the map area, the Brown Mountain fault is a steep reverse fault, with the northeast side relatively upthrown. Displacements of 300 feet can be demonstrated, but the total displacement is not known.

Owl Lake Fault. The Owl Lake fault strikes northeast across the Quail Mountains from its southwest termination at the Garlock fault. Eight miles northeast of the map area it forms a prominent scarp along the southern margin of the Owl Lake basin, where it is a normal fault with the southeast side upthrown relative to the northwest side. In the map area, however, it is a reverse fault with the north side uplifted.

Both the Brown Mountain fault and the Owl Lake fault show evidence of Recent movement in the form of scarplets, undrained depressions, and offset land surfaces.

Acknowledgments. The author is deeply grateful to D. F. Hewett, not only for suggesting and making this study possible, but for devoting many hours to discussions of the problems involved both in the field and in the office. R. H. Jahns, O. P. Jenkins, L. T. Silver, and L. A. Wright also visited the author in the field and offered many valuable suggestions.

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GEOLOGIC MAP AND CROSS SECTION OF THE

ALEXANDER HILLS AREA

INYO AND SAN BERNARDINO COUNTIES,
CALIFORNIA

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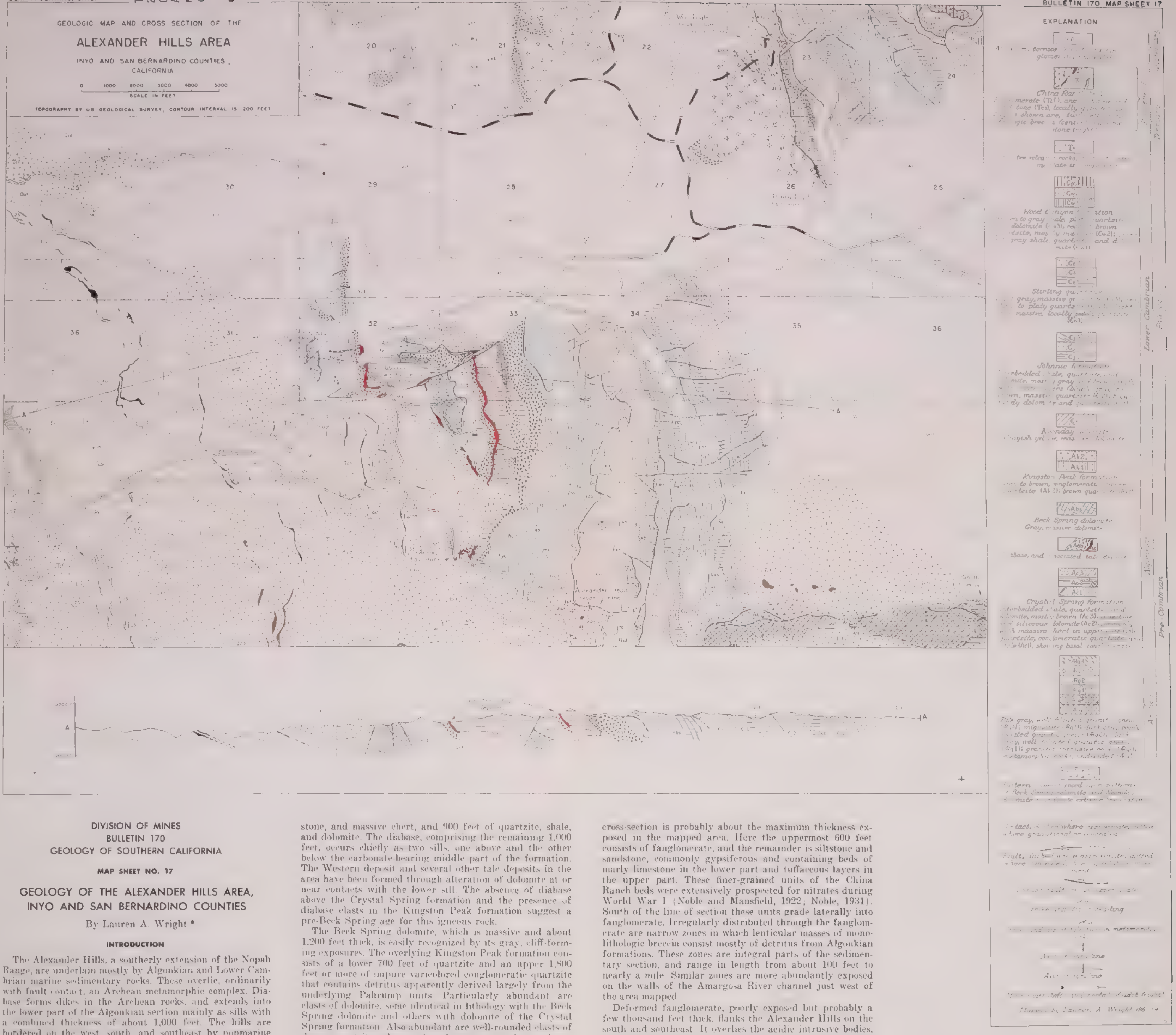
SCALE IN FEET

TOPOGRAPHY BY US GEOLOGICAL SURVEY, CONTOUR INTERVAL IS 200 FEET



DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 17

GEOLOGY OF THE ALEXANDER HILLS AREA, INYO AND SAN BERNARDINO COUNTIES

By Lauren A. Wright *

INTRODUCTION

The Alexander Hills, a southerly extension of the Nopah Range, are underlain mostly by Algonkian and Lower Cambrian marine sedimentary rocks. These overlie, ordinarily with fault contact, an Archean metamorphic complex. Diabase forms dikes in the Archean rocks, and extends into the lower part of the Algonkian section mainly as sills with a combined thickness of about 1,000 feet. The hills are bordered on the west, south, and southeast by nonmarine Tertiary sedimentary rocks that are 5,000 feet or more in total thickness. These are overlain by Quaternary alluvium, some of which has been deeply dissected.

Of particular significance within the mapped area is the presence of one of the thickest and most complete known sections of the Algonkian Pahrump series. The area also contains structural features that bear upon problems of the late Tertiary low-angle thrust faults described in areas to the west and east (Noble, 1941; Hewett, 1954). Also within this area are the Western mine, one of the largest talc operations in California, and the War Eagle mine, part of the Shoshone group of lead-silver-zinc workings which for many years ranked second in California as a source of lead ore.

The general features of the Alexander Hills area have been described and shown in cross section by L. F. Noble (1941, pp. 993-994), who suggested the writer's present study and who has shown a helpful and continuing interest in it. The Amargosa thrust fault, studied in detail by Noble near Virgin Spring in the Black Range, was tentatively projected by him about 28 miles east-southeast into the Alexander Hills area.

ROCK UNITS

Archean (Earlier Pre-Cambrian) Rocks. Archean rocks are extensively exposed west of the War Eagle mine, where they consist of granitic gneiss and migmatite with subordinate amounts of quartzite, mica schist, and amphibolite. They contain irregular bodies of pegmatite and other intrusive granitic rocks, also Archean in age. Archean rocks also are exposed at several places in the Alexander Hills, but underlie much smaller areas.

Most of the gneiss, as well as the quartzite and schist, appears to be metasedimentary and is broadly divisible into units 1,000 to 4,000 feet thick. These can be distinguished by differences in mineralogy and the character of their planar structures, which range from indistinct to pronounced. Except for tilting and local faulting, these Archean units show little large-scale deformation.

Algonkian (Later Pre-Cambrian) rocks. The Pahrump series, composed in upward sequence of the Crystal Spring formation, the Beck Spring dolomite, and the Kingston Peak formation, underlies the west flank of the Alexander Hills and here totals about 8,000 feet in maximum observed thickness. This series, much less metamorphosed than the underlying Archean rocks, contains sedimentary units that persist for great distances horizontally and show abrupt vertical changes in lithology.

Northward from its thickest and most southerly exposures the series is transected by the overlying Lower Cambrian Noonday dolomite, which rests directly upon Archean rocks north of the War Eagle mine. The transection is partly an effect of low-angle thrusting, but the uniformity with which the underlying Algonkian units are cut out strongly suggests that the major feature is an unconformity.

The Crystal Spring formation, here about 4,200 feet thick, is composed from bottom to top of about 1,500 feet of quartzite and shale, 900 feet of cherty dolomite, limestone, and massive chert, and 900 feet of quartzite, shale, and dolomite. The diabase, comprising the remaining 1,000 feet, occurs chiefly as two sills, one above and the other below the carbonate-bearing middle part of the formation. The Western deposit and several other talc deposits in the area have been formed through alteration of dolomite at or near contacts with the lower sill. The absence of diabase above the Crystal Spring formation and the presence of diabase clasts in the Kingston Peak formation suggest a pre-Beck Spring age for this igneous rock.

The Beck Spring dolomite, which is massive and about 1,200 feet thick, is easily recognized by its gray, cliff-forming exposures. The overlying Kingston Peak formation consists of a lower 700 feet of quartzite and an upper 1,800 feet or more of impure varicolored conglomeratic quartzite that contains detritus apparently derived largely from the underlying Pahrump units. Particularly abundant are clasts of dolomite, some identical in lithology with the Beck Spring dolomite and others with dolomite of the Crystal Spring formation. Also abundant are well-rounded clasts of dense quartzite whose original source remains undetermined. As they appear more metamorphosed than the quartzite of the Pahrump series, resemble none of the known Archean rocks of the southern Death Valley region, and are identical with clasts in the lower part of the Crystal Spring formation, they probably have been transported many miles from pre-Pahrump metasedimentary units and may have been partly or wholly reworked.

Paleozoic Rocks. The Paleozoic rocks of the mapped area consist of essentialy the same formations and members that comprise the lower part of the Paleozoic section of the Nopah Range (Hazzard, 1937, pp. 274-288). The Noonday dolomite, Johnnie formation, Stirling quartzite, and the lower part of the Wood Canyon formation, about 6,000 feet in total thickness, are exposed east of the War Eagle mine entrance and in the eastern part of the Alexander Hills. Although unfossiliferous and older than beds that contain Lower Cambrian fossils, this part of the section is generally assigned a Lower Cambrian age (Hazzard, 1937, pp. 300-312).

The Noonday dolomite, a massive, grayish yellow formation about 1,500 feet thick, forms the crest of the Alexander Hills. Although undivided on the accompanying map, this formation has a slightly darker upper half, and commonly contains shaly and quartzitic layers in its middle and upper parts. It is the host rock for almost all of the lead-silver-zinc deposits of the southern Death Valley-Kingston Range region, including the Shoshone group noted above.

The overlying Johnnie formation, about 2,200 feet thick, is divisible into 600 feet of sandy dolomite successively overlain by 300 feet of quartzite and 1,300 feet of interlayered shale, quartzite, and subordinate dolomite.

The Stirling quartzite in the Alexander Hills averages about 2,000 feet in thickness and is divisible into a lower 600-foot massive quartzite member, a middle 600-foot shale and platy quartzite member, and an upper 800-foot massive quartzite member.

In the southern Nopah Range the Wood Canyon formation is about 3,000 feet thick and consists of a lower 250-foot shaly member overlain by about 1,500 feet of quartzite, and an upper 1,250 feet, not shown on the accompanying map, of interlayered shale, quartzite, limestone, and dolomite.

Intrusive Volcanic Rocks. In the southeastern part of the Alexander Hills, irregular bodies of volcanic rocks, acidic to intermediate in composition, are intrusive into the Paleozoic units and are overlain by Tertiary fanglomerate. They probably are of Tertiary age and correlative with similar boides extensively exposed low on the west slope of the Kingston Range several miles to the east.

Tertiary Sedimentary Rocks. The Tertiary sedimentary rocks that border the Alexander Hills are best exposed to the west, where a broadly folded section, mostly siltstone and fanglomerate, has been deeply dissected to a badland topography. These beds have been tentatively correlated with the Pliocene (?) Funeral fanglomerate (Noble, 1941, pp. 992-993) and referred to as the China Ranch beds (Mason, 1948, p. 337).

The 5,000 feet of sediments shown on the accompanying cross-section is probably about the maximum thickness exposed in the mapped area. Here the uppermost 600 feet consists of fanglomerate, and the remainder is siltstone and sandstone, commonly gypsiferous and containing beds of marly limestone in the lower part and tuffaceous layers in the upper part. These finer-grained units of the China Ranch beds were extensively prospected for nitrates during World War I (Noble and Mansfield, 1922; Noble, 1931). South of the line of section these units grade laterally into fanglomerate. Irregularly distributed through the fanglomerate are narrow zones in which lenticular masses of monolithologic breccia consist mostly of detritus from Algonkian formations. These zones are integral parts of the sedimentary section, and range in length from about 100 feet to nearly a mile. Similar zones are more abundantly exposed on the walls of the Amargosa River channel just west of the area mapped.

Deformed fanglomerate, poorly exposed but probably a few thousand feet thick, flanks the Alexander Hills on the south and southeast. It overlies the acidic intrusive bodies, as well as the older crystalline rocks. It appears to be part of the China Ranch beds, and possibly is a much thicker occurrence of the upper fanglomerate unit that is exposed west of the hills. The China Ranch fanglomerates consist mainly of poorly sorted debris of the pre-Tertiary crystalline rocks and Tertiary (?) volcanic rocks. Characteristic are large boulders of granitic rock, as much as 20 feet in diameter, apparently derived from the Kingston Range several miles to the east. Except for the local occurrence of wood fragments and a few bird tracks, the China Ranch beds to date have proved to be unfossiliferous.

Quaternary Rocks. The Quaternary sedimentary rocks, undivided on the accompanying map, consist of well-dissected older fanglomerate and terrace deposits, and alluvium of the present stream channels. All are nearly horizontal, overlie the China Ranch beds with a marked angular unconformity, and are similar to the fanglomeratic facies of these beds. The older fanglomerate, well-exposed in the wash that drains westward from Tecopa Pass, is about 300 feet in maximum observed thickness. North of the map, beds of older fanglomerate overlie Tecopa lake beds (Blackwelder, 1954) of Pleistocene age, and also probably grade laterally into them.

STRUCTURAL FEATURES

Although the area shown on the map is relatively small, its structural features may well prove to be significant in future regional studies. The pre-Tertiary rocks within the area have been deformed mainly by faulting, and the deposits show little, if any, deformation. Most of the major faults apparently pre-date the China Ranch beds, and lie partly or wholly beneath them or beneath Quaternary deposits.

Noble (1941, p. 958) and Mason (1948, pp. 342, 351) conclude that the rocks of the Nopah Range and Alexander Hills were deformed principally during two major stages in Tertiary time, the first marked by low-angle thrusting, primarily of younger over older rocks, and the second marked by high-angle normal faults.

The contact between the Archean complex and overlying Pahrump units, which Noble (personal communication) has suggested as the possible position of the Amargosa thrust, is ordinarily highly brecciated and moderately to gently dipping. Only at one locality, near the most westerly shaft of the Western mine, is the contact clearly depositional. Elsewhere from a few hundred to several thousand feet of Pahrump strata have been cut out. Within the Pahrump and Paleozoic sections major lithologic breaks also are commonly brecciated, and at several places large, steeply dipping blocks rest, with a low-angle contact, upon older strata. This relationship is shown by a block of Beck Spring dolomite upon the upper units of the Crystal Spring formation, and by blocks of the Noonday formation upon the Kingston Peak formation and Beck Spring dolomite. In the northeast corner of the map area, part of a klippe of Wood Canyon quartzite rests upon quartzite lower in the same formation. Near the center of the map area outliers of breccia, composed mostly of Noonday dolomite and resting upon the Crystal Spring formation, appear to represent additional klippe, but may be of sedimentary origin.

Regardless of these thrust faults, the sedimentary section of the Alexander Hills apparently is almost intact, and it is not nearly so disordered as the chaos above the Amargosa thrust as exposed in the Virgin Spring area about 30 miles to the northwest. Displacements of a mile or less could have produced most of the features noted above. However, thrusting may have involved greater displacements along a west-trending, 2-mile belt in the southeastern part of the hills, where the carbonate member of the Crystal Spring formation and fault-breccia zones of Beck Spring dolomite and Noonday dolomite each rest upon Archean rocks. In the War Eagle mine area a sliver of impure, conglomeratic quartzite, lying between Archean granitic gneiss and Noonday dolomite and also faulted into the dolomite (Hazzard, 1939), resembles the upper member of the Kingston Peak formation. If the correlation is valid, the underlying Pahrump units either were eroded in earlier Pahrump time or have been faulted out. The quartzite, however, may be a basal facies of the Noonday dolomite. That it is relatively unbrecciated suggests that the faults bordering it are not major thrusts.

Numerous cross faults cut the pre-Tertiary rocks, but rarely show displacements of more than 400 feet. One that trends westward beneath the alluvium of Tecopa Pass has an apparent horizontal offset of about 2½ miles in a right-lateral sense. This fault appears to be cut by a younger northeast-trending fault which has a maximum apparent horizontal offset of about a mile in the northwestern part of the Alexander Hills. It dies out in Paleozoic rocks about 6 miles northeastward at a point north of the War Eagle mine. As the movement is left-lateral, much of the thrusting in the Alexander Hills may be an effect of shortening on the southeast side of this fault. That it is not a rotational fault with a large displacement is indicated by the drag fold in the northwestern part of the Western mine area.

The easterly dip of the Pahrump and Paleozoic units is attributable largely or wholly to tilting along one or more normal faults hidden beneath the Tertiary and Quaternary cover to the west.

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DIVISION OF MINES
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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 170 MAP SHEET 18

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24
C3
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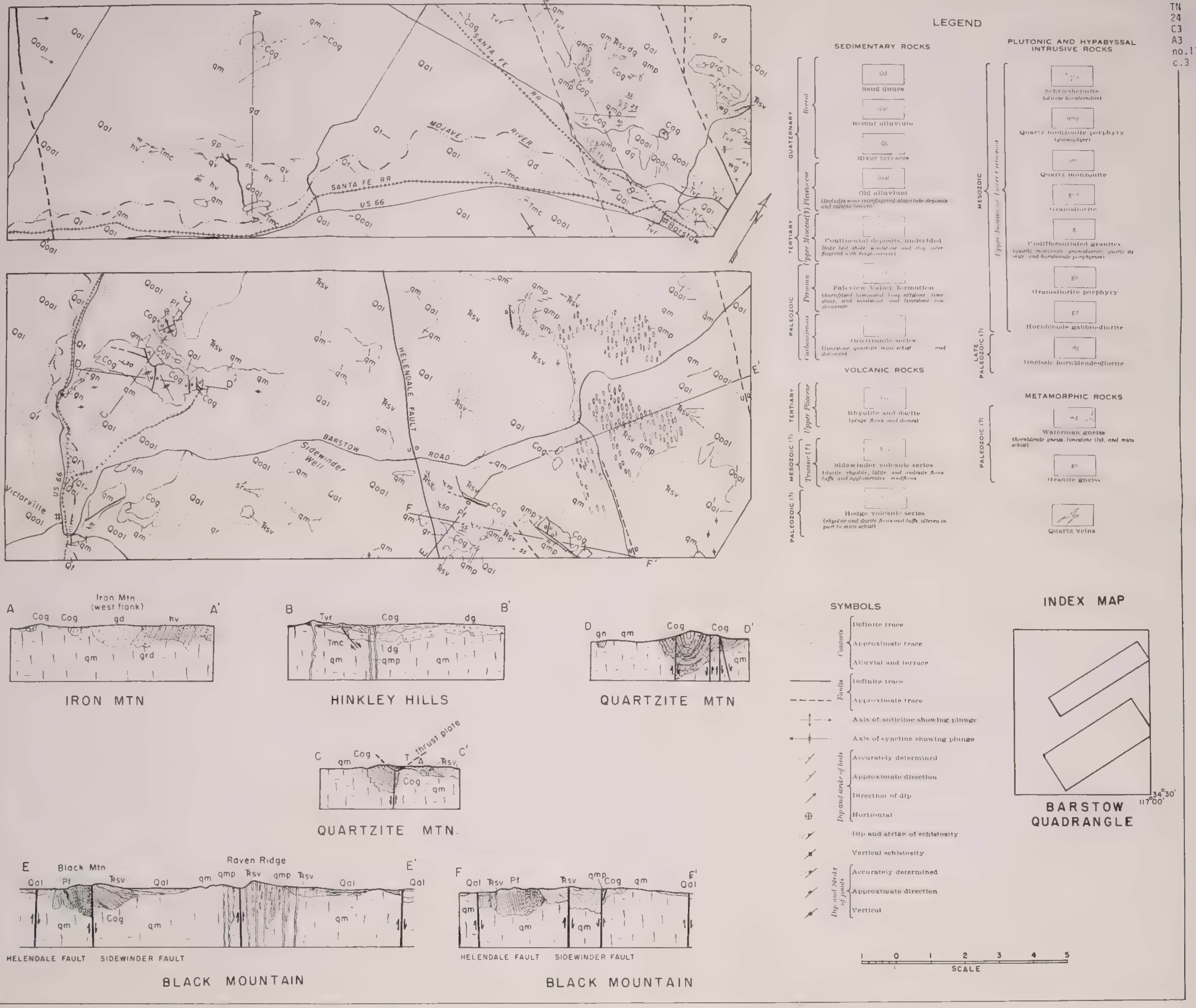
LEGEND
SEDIMENTARY ROCKS
QUATERNARY
Recent
Qd Sand dunes
Qal Recent alluvium
Qt River terraces
Pleistocene
Qoal Old alluvium (includes some interfingered playa lake deposits and caliche breccia)
TERTIARY
Upper Miocene(?)
Continental deposits, undivided (lake bed shale, siltstone and clay, interfingered with fanglomerate)
PALEOZOIC
Permian
Fairview Valley formation (hornfelsed laminated limy siltstone, limestone, and sandstone and limestone conglomerate)
Carboniferous
Oro Grande series (limestone, quartzite, mica schist and dolomite)
VOLCANIC ROCKS
TERTIARY
Upper Pliocene
Rhyolite and dacite (plugs, flows, and domes)
MESOZOIC (?)
Triassic (?)
Sidewinder volcanic series (dacite, rhyolite, latite, and andesite flows, tuffs, and agglomerates, mudflows)
PALEOZOIC (?)
Hodge volcanic series (rhyolite and dacite flows and tuffs, altered in part to mica schist)
PLUTONIC AND HYPABYSSAL INTRUSIVE ROCKS
MESOZOIC
Upper Jurassic or Lower Cretaceous
Schriesheimite (olivine hornblendite)
qmp Quartz monzonite porphyry (granophyre)
qm Quartz monzonite
grd Granodiorite
g Undifferentiated granites (quartz monzonite, granodiorite, quartz diorite, and hornblende porphyries)
gp Granodiorite porphyry
gd Hornblende gabbro-diorite
LATE PALEOZOIC (?)
dg Gneissic hornblende-diorite
METAMORPHIC ROCKS
PALEOZOIC (?)
wg Waterman gneiss (hornblende gneiss, limestone (ls), and mica schist)
gn Granite gneiss
qv Quartz veins
SYMBOLS
Contacts
Definite trace
Approximate trace
Alluvial and terrace
Faults
Definite trace
Approximate trace
Axis of anticline showing plunge
Axis of syncline showing plunge
Dip and strike of beds
Accurately determined
Approximate direction
Direction of dip
Horizontal
Dip and strike of schistosity
Vertical schistosity
Dip and strike of joints
Accurately determined
Approximate direction
Vertical
INDEX MAP
34°30'
117°00'
BARSTOW QUADRANGLE
0 1 2 3 4 5
SCALE
SANTA FE RR
MOJAVE RIVER
US 66
BARSTOW
HELENDALE FAULT
BARSTOW ROAD
Sidewinder Well
Victorville
A A' Iron Mtn (west flank)
IRON MTN
B B'
HINKLEY HILLS
D D'
QUARTZITE MTN
C C' thrust plate
QUARTZITE MTN
E E' Black Mtn Raven Ridge
HELENDALE FAULT SIDEWINDER FAULT
BLACK MOUNTAIN
F F'
HELENDALE FAULT SIDEWINDER FAULT
BLACK MOUNTAIN

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 18

GEOLOGY OF THE BARSTOW AREA, SAN BERNARDINO COUNTY

By Oliver E. Bowen, Jr.*

The part of the Mojave Desert region described herein lies south of Harper Dry Lake, north of the San Bernardino Mountains, and between the Shadow and Ord Mountains. Barstow is near the northeast corner and Victorville near the southwest corner of the area. The broad arc of the Mojave River is the dominant geographic feature, and the topography ranges from subdued hills to mountainous buttes that are separated by moderate to broad areas of alluvial fill. In general the mountains and hills are arranged in a northwest-trending pattern that is structurally controlled.

ROCK TYPES

Pre-Cenozoic Rocks. Pre-Cretaceous metasedimentary and metavolcanic rocks occur discontinuously as large and small roof pendants suspended in a variety of granitic rocks. Tertiary volcanic and nonmarine sedimentary rocks, none of them older than middle Miocene, occur as erosion remnants or in tilted and down-dropped fault blocks. None of the outcrop areas of these rocks are greater than three square miles in extent. Pleistocene and Recent alluvium, although lithologically similar in most places, are separable over wide areas because Recent regional uplift has caused dissection of the Pleistocene deposits and development of new plains of aggradation.

The oldest rocks in the area probably are the marine metasedimentary rocks of the Oro Grande series, which was first described by Hershey (1902) and was further discussed briefly by Baker (1911), Darton (1915), and Miller (1944). Part of the Hodge volcanic series may be older than some of the Oro Grande rocks, but the two rock groups are not in contact. The Oro Grande series is largely or wholly Carboniferous in age, as shown by round crinoid stems, brachiopods, and crinoid and brachiopod debris obtained from its lower part. It is unconformably overlain by the Permian Fairview Valley formation.

The series consists predominantly of massive blue-gray to white carbonate rocks (chiefly limestone), massive pink to lavender quartzite, and brown to black biotite-quartz schist. Locally included are quartz-muscovite schists and gneisses, brown quartz-biotite hornfels, laminated impure green quartzite, and almost unmetamorphosed calcareous sandstones and siltstones. Dolomite is abundant in the lower part of the series, and some dolomitic strata are present locally in the upper part.

Typical sections of Oro Grande rocks occur on the east face of Quartzite Mountain near Oro Grande, and in the Shadow Mountains northwest of Adelanto. These have exposed thicknesses of 2,650 feet and 9,670 feet, respectively.

Exposed north of Barstow and southeast of the Waterman silver mine is the Waterman gneiss, a coarse-grained hornblende-andesine gneiss that probably is a metamorphosed hornblende diorite intrusive into the Oro Grande series. A 4,000-foot thickness of the gneiss, exposed beneath the Oro Grande series in the Waterman anticline, contains large inclusions of Oro Grande rocks. It has been partly mylonitized in a severe deformation unparalleled elsewhere in the Barstow area, and is believed to have been intruded and deformed in late Paleozoic time.

The Hodge volcanic series, named from a 10,000-foot homoclinal section exposed 2 to 3 miles northwest of Hodge (Bowen, 1954), is an isolated group of rocks in contact only with granitic rocks and with Tertiary and Quaternary alluvium. It has been intruded by quartz monzonite, granodiorite porphyry, and a variety of small granitic dikes. The series has a structural trend that probably was imposed during the end-Paleozoic disturbance. Lenses of pale pink quartzite, lithologically similar to quartzite in the Oro Grande series, occur in the upper part of the section. As this series is more highly metamorphosed than the rocks of the Triassic (?) Sidewinder series described below, it probably is upper Paleozoic in age.

The lower half of the Hodge series consists principally of massive reddish-brown, purplish-brown, and dark green quartz latite and dacite that have been mildly sheared, and was originally a sequence of vitrophyric flows and crystal-lithic-vitric tuffs. The upper half of the series consists of alternating masses of pearly white, black, and gray-green metavolcanic rocks that have been strongly sheared. They contain thin lenses of metasediments. Muscovite schist, muscovite-quartz-biotite schist, and biotite-quartz schist are the prevailing rock types. The original rocks probably were in part water-laid.

Unconformably overlying the Oro Grande series west and north of the Reserve quarry of the Southwestern Portland Cement Company is the Permian marine Fairview Valley formation, named from adjacent Fairview Valley (Bowen, 1954). This formation consists of a lower member, composed mostly of banded hornfelsic and calcareous siltstone 4,725 feet in aggregate thickness, and an upper limestone conglomerate member that is 1,350 feet thick. The rocks of the banded hornfels member are mostly pale gray-green to white on fresh surfaces, and commonly weather to rusty brown. Thin lenses of black limestone, gray sandstone, reddish conglomerate, and coarse, dark-gray calcarenites occur locally in the hornfels member.

The limestone conglomerate member consists almost wholly of limestone cobbles, pebbles, and boulders that are cemented by calcium carbonate and minor silica. The clasts contain an abundant Permo-Carboniferous coral-echinoid-brachiopod-gastropod fauna, including several genera diagnostic of the Lower Permian. Only a few fossils have been taken from the matrix, and these also may be detrital; thus there is some doubt that the fossils are contemporaneous with the formation as a whole. The Fairview Valley formation is regarded as Permian (?) in age, probably Middle or Upper Permian.

Overlying the Fairview Valley section and in places intruding it is the Sidewinder volcanic series, a flow and pyroclastic assemblage that was deposited subaerially on a very uneven topography. The series was named from extensive exposures on Sidewinder Mountain, where it is probably as much as 4,000 feet thick (Bowen, 1954). Rocks of this volcanic assemblage overlap the eroded edges of the Oro Grande series, as well as the Fairview Valley formation. Rocks of similar age and appearance are broadly distributed in the Barstow region from the Kramer borate district southeastward through the Ord Mountains. Dacite and rhyolite are the dominant rock types, and latite and andesite are much less common. Pink, red, white, black, and green colors are prominent from place to place, the amount of coloration generally being dependent upon the degree of alteration. Red and pink dacites on Sidewinder Mountain commonly contain piedmontite as a late hydrothermal product, and locally thulite is present. Between Sidewinder Mountain and the Sidewinder mine a large lahar or mud-flow conglomerate occurs in the series.

A wide variety of granitic rocks intrudes all of the units described above. Only one of these intrusive rocks, a gneissic hornblende diorite exposed in the Hinkley Hills, is believed to be older than Jurassic; it probably is equivalent in age to the Waterman gneiss. It intrudes the Oro Grande series and is much more severely deformed than the other granitic rocks, which probably were intruded in Upper Jurassic or Lower Cretaceous time. Of these, biotite quartz monzonite is the most extensively exposed, but stocks of granodiorite, hornblende gabbro-diorite, and granodiorite porphyry also are present. Other granitic rocks generally occur as smaller masses. The Jura-Cretaceous sequence of intrusion, from oldest to youngest, was: gabbro-diorite, granodiorite and granodiorite porphyry, quartz monzonite and quartz monzonite porphyry, schriesheimite (olivine hornblendite), lamprophyres, and granite aplite and pegmatite.

Cenozoic Rocks. Middle and upper Miocene continental sedimentary and volcanic rocks occur mainly in the Kramer and Hinkley-Waterman Hills. None of the isolated patches of these rocks have yielded diagnostic fossils as yet, and lithologic correlations can be made only in the broadest terms. The thickest Miocene section, composed of about 4,800 feet of lake beds and interlayered flows of quartz andesite, occurs in the Kramer Hills. These rocks have been intruded by Miocene (?) dikes and sills of olivine analcite diabase, and also have been intruded and unconformably overlain by upper Pliocene dacite. At the Waterman mine, 4 miles north of Barstow, 2,000 feet of interbedded red, maroon, and chocolate-brown lake-bed and fanglomerate sediments are unconformably overlain by red dacite.

Upper Pliocene red and gray dacite, which occurs as plugs, flows, and dikes, is broadly distributed in the northern third of the Barstow quadrangle. It is most conspicuously exposed in the vicinity of the town of Barstow, and in the Waterman and Hinkley Hills. Where they are in contact with Miocene continental sediments, these Pliocene volcanic rocks overlie the sediments with a marked angular unconformity. They are undeformed or very gently deformed, in contrast to the older rock units. They are lithologically similar and bear similar structural relationships to the upper Pliocene dacitic volcanic rocks of the Calico and Lane Mountain areas.

Pleistocene alluvium is well exposed in the Palisades of the Mojave River in and north of Victorville, where scattered mammalian remains serve to date the deposits. The section is 800 feet or more thick southwest of Victorville, where it has been penetrated by wells. Elsewhere in the area the Pleistocene alluvium can be distinguished from Recent alluvium of similar appearance because it has been uplifted and dissected. North of the Mojave River in the Helendale area, Pleistocene alluvium interfingers with lacustrine shales, opaline shales, and marls that mark the site of a former playa.

STRUCTURE

An active, northwest-trending fault system is the dominant structural feature of the area. Both normal and lateral movements are recognizable along faults of this system. The most persistent fault, the Helendale, is traceable for 40 miles from Cushenbury Canyon in the San Bernardino Mountains to the Kramer Hills.

Pre-upper Pliocene overthrusting, of significant magnitude and northwest trend, has occurred along the front of the Waterman Hills north of Barstow. An erosional remnant of a probably related thrust plate is present 1½ miles west of the principal fault trace. A folded thrust plate is present on the north slope of Quartzite Mountain east of Oro Grande. Also exposed in the area are a northwest-trending fault system of pre-Upper Jurassic age and a northeast-trending system of probable Quaternary age.

The largest fold in the area is only partly preserved, and is represented by an arcuate homocline that is convex to the northwest. It probably was developed at the close of the Paleozoic era. The southeastern limb of this fold has been eroded away or obliterated by igneous intrusion. The course of the Mojave River through the quadrangle has been controlled largely by elements of this ancient structure. With the exception of intense folding in a few areas such as the Waterman and Hinkley Hills, broad and relatively simple folds with northeast- or east-trending axes were typically developed in the end-Paleozoic orogeny. These folds are in sharp contrast to the acute, northwest-trending folds characteristic of the later Jura-Cretaceous orogeny.

Intense folding and faulting in lower and middle Pliocene time have affected the Miocene sections in nearly all areas where they are exposed. Gentle arching of Recent age, probably related to the principal northwest fault system, has affected Pleistocene and upper Pliocene rocks. The Recent regional uplift, noted above in connection with the alluvium in the area, amounted to at least 200 feet and caused deep dissection of former Pleistocene surfaces.

Capture by Cajon Creek of part of the San Bernardino Mountains drainage of the Mojave River has radically changed the pattern of the Mojave River tributaries in the southwestern part of the area. A probable southeast-flowing stream system, draining from what is now the Lucerne Valley area toward the Colorado River, has been destroyed by Quaternary diastrophism. Exhumed remnants of Miocene land surfaces are present north of the Mojave River, in the vicinity of Hodge and Barstow, and relict Pleistocene surfaces are preserved east of Oro Grande. A lake existed in fairly recent time south of the Upper Narrows of the Mojave River at Victorville.

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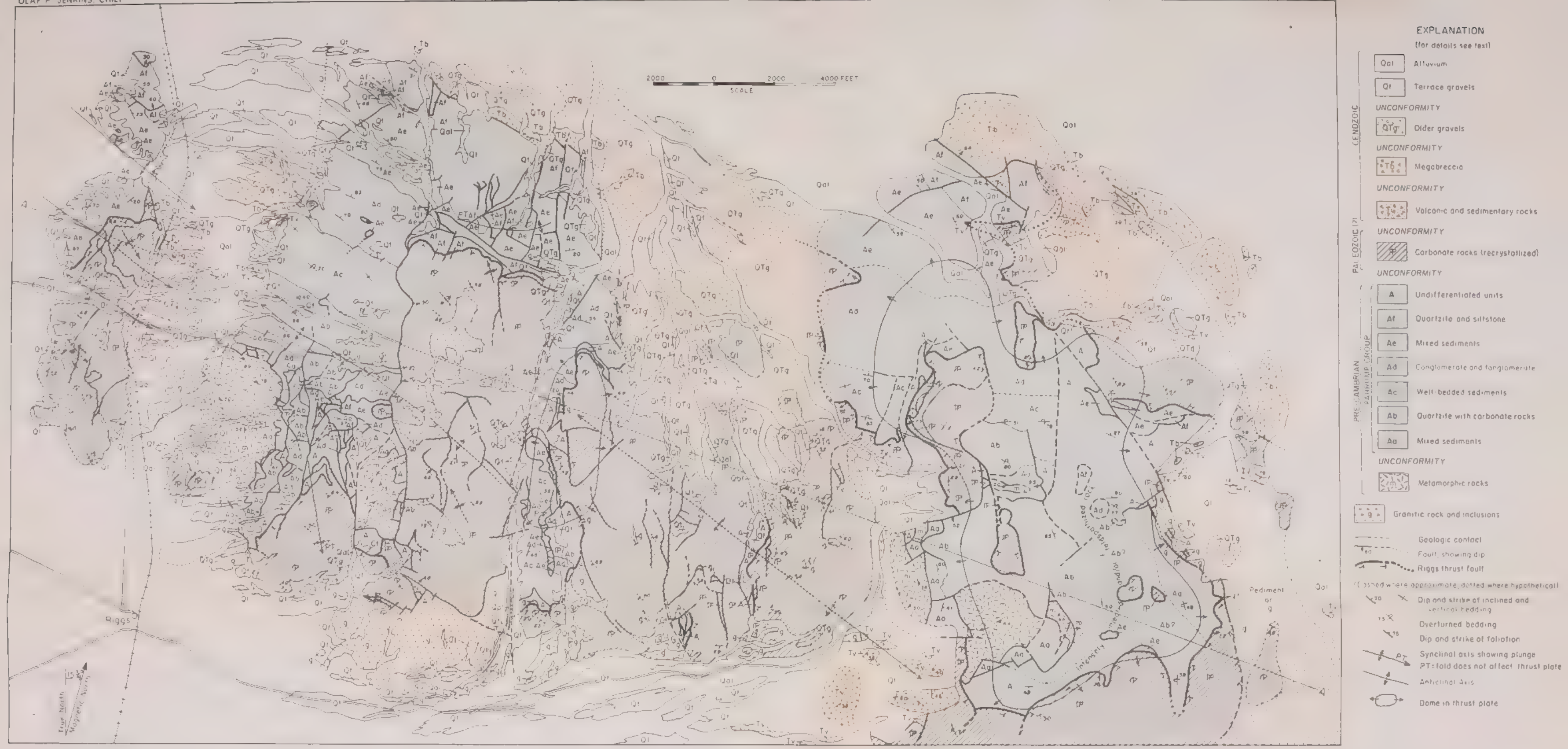
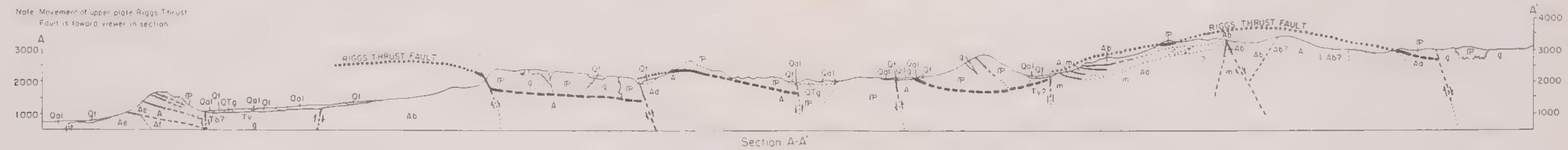
BULLETIN 170 M S 19




Note: Movement of upper plate Riggs Thrust Fault is toward viewer in section
A
A'
RIGGS THRUST FAULT
4000
3000
2000
1000

Section A-A'

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 19

GEOLOGY OF THE SILURIAN HILLS, SAN BERNARDINO COUNTY *

By Donald H. Kupfer †

The Silurian Hills, 15 miles southeast of Death Valley, are composed principally of pre-Cambrian rocks (older metamorphic rocks and Pahrump group) beneath the Riggs thrust, and of recrystallized Paleozoic(?) carbonate rocks above the thrust. Along the northern border a monolithologic megabreccia composed of Paleozoic carbonate rocks (mostly Goodsprings dolomite) rests unconformably on folded Cenozoic volcanic and sedimentary rocks, as well as on the older rocks. These are all unconformably overlain by fan gravels and terrace gravels of several ages.

The Pahrump rocks in the Silurian Hills are 11,000 feet thick and have been subdivided into 35 mappable members. They are composed chiefly of coarse clastic rocks, and the top of the section is not exposed. The members have been combined into six units on the accompanying map, and the marker beds, aplite dikes, diabase sills, and talc bodies have been omitted. At the type area (Hewett, 1940) in the Kingston Range, 15 miles to the north, the fine-grained clastic and carbonate rocks of the Pahrump series (herein termed group in accordance with the stratigraphic code of Ashley, et al., 1933) have been subdivided into three formations. Correlation between the two areas is uncertain, but the six basal members in the Silurian Hills (unit "Aa" on the map), with their included diabase sill and talc horizon, can be correlated lithologically with the basal part of the type section. A sediment source to the south is indicated by the increasing coarseness of the rocks in this direction, as well as by minor sedimentary structures.

Igneous intrusion, lit-par-lit injection, and feldspathization of the older rocks are common throughout the mapped area. Below the Riggs thrust distinctive members of the Pahrump group can be traced, with minor interruptions, from relatively unmetamorphosed sedimentary rocks in the west to intensely feldspathized and intruded rocks, called "Archean" by earlier workers, in the east. Above the thrust all the carbonate rocks have been recrystallized, and the most intensely metamorphosed rocks occur in the west-central part of the area.

The Riggs thrust is apparently localized along the relatively horizontal surface of angular unconformity between the Paleozoic(?) carbonate rocks and the Pahrump rocks. The thrust surface is dome shaped, probably because of post-thrust warping. The rocks beneath the thrust plate have been sliced into giant blocks 50 to 1,000 feet long, and have been piled up into an imbricate or chaos structure (Noble, 1941) in which the original stratigraphic order is crudely maintained. The blocks are now a few feet to a mile or more from their original source to the north-northeast. The direction of movement of the individual blocks, drag structures, and subsidiary faults indicates that the thrust plate moved south-southwest. The amount of movement of the plate has not been determined, but from the distribution of granitic rocks in the plate and sole it is estimated to be about eight miles.

High-angle faulting and igneous intrusion occurred before, during, and after the thrust faulting, but chiefly prior to the thrusting. The Riggs thrust cannot be closely dated, but the Cenozoic volcanic rocks are folded and confined to the plate, which suggests that the essentially unfolded thrust is younger. If, however, the volcanic rocks were folded by the same superficial forces that led to development of the overlying megabreccia, the Riggs thrust need not have been folded even though it were much older.

The topography of the area is closely controlled by rock type and structure. There is no evidence of Recent tectonic movement. The high peaks and ridges are capped by resistance carbonate rocks of the thrust plate, and the valleys have been cut in the easily eroded Pahrump rocks and/or localized along the high angle faults. A marked west-facing obsequent scarp can be seen from the Death Valley highway.

Talc and silver have been mined in the area. Talc, which can be seen as white patches from the highway, occurs as a replacement of carbonate rocks adjacent to diabase sills in the basal part of the Pahrump group. The lead-silver minerals are in the Paleozoic(?) carbonate rocks at the intersections of north- to northeast-trending high-angle faults with the top of what is thought to be a single bed of limestone. The Riggs silver mine, in the southwest corner of the area, is reported to have had an output valued at $200,000, probably from secondarily enriched ores.

STRATIGRAPHIC SECTION

Map symbol	Field unit	Description
Qal	Alluvium	Stream gravels and recent alluvial-fan gravel
	Sand	Wind-blown sand
	Regolith	Regolith and talus
	Slump blocks	Landslides and landslump blocks and associated breccia
Qt	Terrace gravels	Terrace gravel of at least four ages
QTg	Older gravels	White granitic fan gravel
	Pink gravels	Volcanic and granitic fan gravel and coarse-grained sand
Tb	Megabreccia	Monolithologic megabreccia of Paleozoic (?) carbonate rock
Tv	Sediments	Well-bedded red, brown, and white gravel, sand, and silt
	Volcanics	Lavas and associated volcanic rocks
	Chert	Radiolarian chert
g	Granitic rock	Porphyritic quartz monzonite and other granitic rock
	Inclusions	Roof-pendants, xenoliths, and/or autoliths of feldspathized sediments, schist, and other mafic aggregations in the granitic rock
P	Limestones	White, gray, and tan well-bedded marble
	Dolomites	Buff to brown, generally brecciated, dolomitic marble
	Mixed carbonates	Interbedded limy and dolomitic marble
	Clastic sediments	Fine-grained, thin-bedded sedimentary rocks
	Quartzites	Vitreous quartzite
A	Undifferentiated	Undifferentiated pre-Cambrian Pahrump rocks, generally part of the chaos structure

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STRATIGRAPHIC SECTION—Continued

Map symbol		Description	Approximate thickness in feet
Af	Member 35	Gray carbonate rock and shale	60
	34	Shale	40
	33	Massive vitreous quartzite with pinkish cast	180
	32	Dolomite, weathering dark chocolate brown	90
	31	Cross-bedded quartzite	950
	30	White vitreous quartzite	220
	29	Black silicified siltstone	110
	28	White vitreous quartzite	50
	27	Black silicified siltstone	30
	26	Vitreous quartzite	80
Ae	Member 25	Orange-weathering dolomite	270
	24	Vitreous, gray, granular quartzite	185
	23	Red-brown quartzite, iron-rich cement	200
	22	Granular quartzite and siltstone	225
	21	Clastic sediments with graded bedding	700
	20	White slabby limestone	25
	19	Impure quartzite, some conglomerate	475
Ad	Member 18	Coarse conglomerate and fanglomerate with amphibolitic boulders and cobbles	1,150 (?)
	17	Coarse conglomerates cut by amphibolitized sill	1,000 (?)
Ac	Member 16	Coarse-grained clastic rocks with graded bedding	370
	15	Medium-grained clastic rocks with graded bedding	370
	14	Fine-grained clastic rocks with graded bedding and much epidote	700
	13	Mixed sedimentary rocks	390
Ab	Member 12	Blue-gray limestone	150
	11	Quartz-pebble conglomerate	430
	10	Sandstone and carbonate rocks	100
	9	White quartzite and quartz-cobble conglomerate	600
	8	Limy sandstone and limestone	100
	7	White quartzite	320
Aa	Member 6	White limestone beds in quartzite	255
	5	Orange-weathering dolomite beds in quartzite	130
	Talc	Talc, foliated or slabby	45
	Diabase	Diabase sill, massive	150
	Member 4	Orange-weathering dolomite	44
	3	Phyllite, siltstone, and sandstone	96
	2	Granular white quartzite	175
	1	Conglomerate with pebbles and cobbles of quartz	75
		Total	10,950 feet
m	Metamorphics	Pre-Pahrump schist, gneiss, schistose quartzite, and granitic rock	

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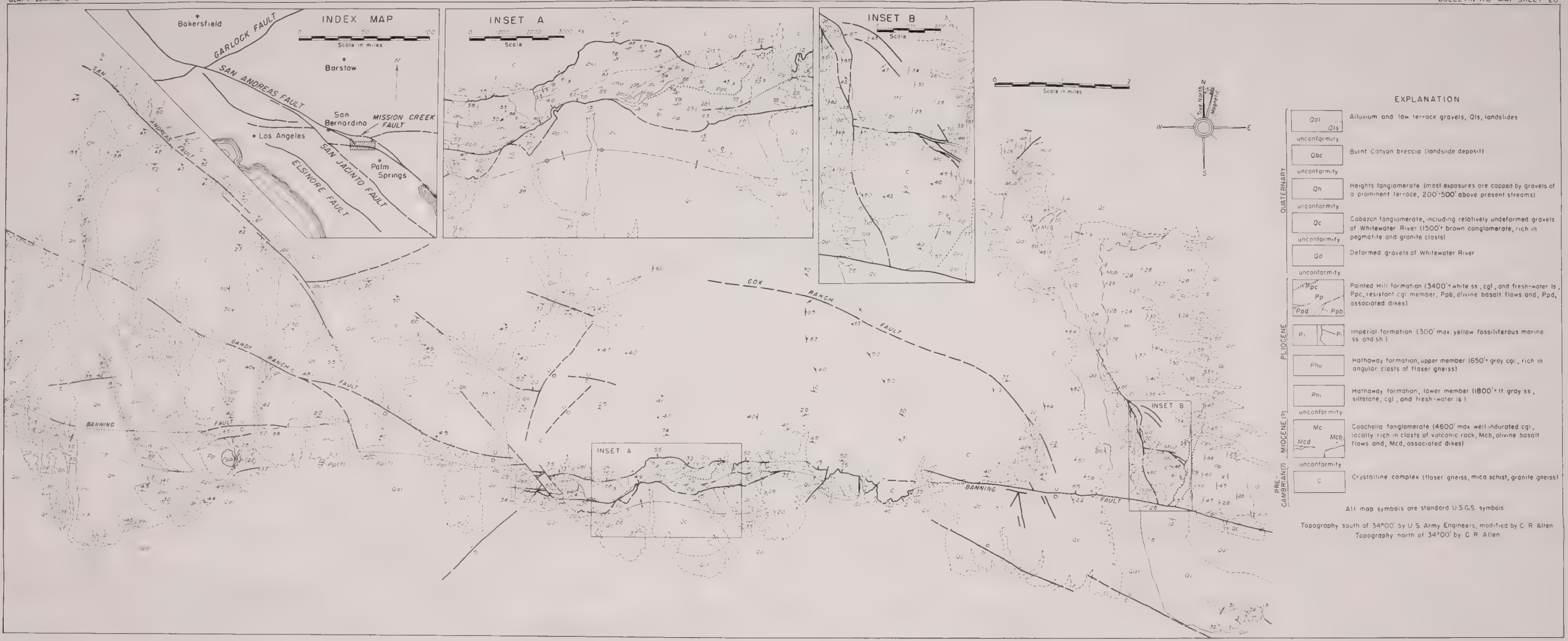
* Extract from a thesis as partial fulfillment of the requirements for the degree of Doctor of Philosophy at Yale University.

† Geologist, Claremont, California.


INDEX MAP
Scale in miles
0
50
100
Bakersfield
GARLOCK FAULT
Barstow
SAN ANDREAS FAULT
San Bernardino
MISSION CREEK FAULT
Los Angeles
SAN JACINTO FAULT
ELSINORE FAULT
Palm Springs
N
INSET A
0
1000
2000
3000 ft
Scale
INSET B
Scale
Scale in miles
0
1
2
True North
Magnetic
W
E
N
S
SAN ANDREAS FAULT
GANDY RANCH FAULT
COX RANCH FAULT
BANNING FAULT
INSET A
INSET B
EXPLANATION
QUATERNARY
Qal Qls — Alluvium and low terrace gravels, Qls, landslides
unconformity
Qbc — Burnt Canyon breccia (landslide deposit)
unconformity
Qh — Heights fanglomerate (most exposures are capped by gravels of a prominent terrace, 200'-500' above present streams)
unconformity
Qc — Cabezon fanglomerate, including relatively undeformed gravels of Whitewater River (1500'+ brown conglomerate, rich in pegmatite and granite clasts)
unconformity
Qd — Deformed gravels of Whitewater River
unconformity
PLIOCENE
Ppc Pp Ppd Ppb — Painted Hill formation (3400'+ white ss, cgl, and fresh-water ls; Ppc, resistant cgl member, Ppb, olivine basalt flows and, Ppd, associated dikes)
Pi — Imperial formation (300' max. yellow fossiliferous marine ss and sh)
Phu — Hathaway formation, upper member (650'+ gray cgl., rich in angular clasts of flaser gneiss)
Phl — Hathaway formation, lower member (1800'+ lt. gray ss, siltstone, cgl, and fresh-water ls)
unconformity
MIOCENE (?)
Mc Mcd Mcb — Coachella fanglomerate (4600' max. well indurated cgl, locally rich in clasts of volcanic rock; Mcb, olivine basalt flows and, Mcd, associated dikes)
unconformity
PRE-CAMBRIAN(?)
C — Crystalline complex (flaser gneiss, mica schist, granite gneiss)
All map symbols are standard U.S.G.S. symbols
Topography south of 34°00' by U.S. Army Engineers, modified by C. R. Allen
Topography north of 34°00' by C. R. Allen

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 20

GEOLOGY OF THE NORTH SIDE OF SAN GORGONIO PASS, RIVERSIDE COUNTY *

By Clarence R. Allen †

The San Andreas fault zone, as it is exposed in San Gorgonio Pass, is distinguished by several unusual features. Among these are the absence of typical rift topography along much of the supposed trace of the fault (Lawson, 1908; Vaughan, 1922), a lack of horizontal stream offsets, an apparent abrupt major change in trend of the fault, and the absence of intense earthquake activity associated with the fault zone. Further, seismic strain-release studies (Dehlinger, 1952) have indicated thrusting, rather than strike-slip faulting, in this one segment of the San Andreas system.

Rock Types. Nearly all the sedimentary rocks exposed in the vicinity of San Gorgonio Pass represent alluvial-fan and lacustrine deposits derived from fault-block mountains to the north. These deposits show marked lateral variations and other stratigraphic complexities that appear to reflect a history of recurrent deformation and deposition in this general area.

The oldest of the sedimentary units, the Coachella fanglomerate, comprises lenticular beds of highly indurated sandstone, conglomerate, and breccia, with interlayered flows of olivine basalt. Much of the rock is considerably jointed and otherwise deformed, and it is probably at least as old as upper Miocene. Younger than the Coachella fanglomerate, although nowhere in contact with it, is the Hathaway formation. This unit consists of a lower member of gray sandstone, siltstone, conglomerate, and fresh-water limestone, overlain by a lenticular upper member of conglomerate and breccia that is rich in clasts of flaser gneiss. The Painted Hill formation ("Indio" formation of Bramkamp, 1934) contains much material secondarily derived from the Coachella fanglomerate. It is typically an unconsolidated gray conglomerate, but it locally contains white sandstone, fresh-water limestone, and interlayered flows of olivine basalt.

Pliocene incursion of marine waters into the Salton Trough (Woodring, 1932; Bramkamp, 1934; Durham, 1950) is represented by a thin section of the Imperial formation, which pinches out north of Painted Hill and west of Deep Canyon. This unit consists chiefly of deep yellowish to brownish sandstone, siltstone, and shale. North of the Banning fault, it lies unconformably on both the Coachella fanglomerate and the much older complex of crystalline rocks. The Painted Hill formation overlies the Imperial formation with essential conformity, even though the Imperial beds pinch out to the north. South of the Banning fault, the Imperial formation is conformable with both the underlying Hathaway formation and the overlying Painted Hill formation, although the entire section is overturned.* It is possible, but not probable, that the two areas of present exposure of the Imperial formation once were contiguous, and have since been offset along the Banning fault.

The Pliocene and Quaternary beds south of the Banning fault consist of material that has been derived mainly from crystalline rocks of the San Gorgonio igneous-metamorphic complex to the north. A body of distinctive piedmontite-bearing gneiss, apparently localized near Stubby and Whitewater Canyons, has contributed to Pliocene sedimentary rocks whose present position with respect to the source area is most reasonably explained by 5 miles of post-Pliocene right-lateral displacement along the Banning fault.

Preliminary reconnaissance of the complex of crystalline rocks indicates that flaser gneiss is the most widespread rock type in the foothills, although biotite schist and granite gneiss become more prevalent to the north. The flaser gneiss is made distinctive by porphyroclasts of carlsbad-twinned orthoclase, many of which are more than two inches long. The crystalline complex is transacted by numerous pegmatite dikes, and many of those east of Lion Canyon are distinguished by their high content of ilmenite.

Geomorphic Features. Extensive surfaces of low relief are being dissected along the south and southeast flanks of San Gorgonio Peak. Erosion in the foothills area has been particularly rapid in the shattered crystalline rocks along the Banning fault, and has produced a prominent fault-line scarp that extends from Potrero Canyon west to Yucaipa Valley. North of Banning, a widespread and relatively undeformed terrace has been developed on Heights fanglomerate, and this surface can be traced eastward beyond the mouth of Millard Canyon, where terrace gravels lie with marked angular unconformity on Cabezon fanglomerate. Near Whitewater, the Cabezon fanglomerate is itself capped by a conformable layer of red soil; this layer has been extensively warped, and at present is being submerged by alluvium east of Painted Hill. The anomalous radial drainage pattern on Beacon Hill, together with the quaquaversal dips of both the fanglomerate and the capping layer of weathered material, indicate that folding is taking place here at the present time.

Upwarping of the San Gorgonio mountain mass is suggested by the positions of terraces in both Banning and Whitewater Canyons. These terrace surfaces rise to markedly greater and greater heights above the present streams as traced in the upstream direction. Warping near the Banning fault evidently was responsible for development of Dry Lake, a large closed basin on the ridge west of Stubby Canyon. Deep fillings of gravel in most of the canyons, especially Whitewater Canyon, suggest that these stream courses were determined in a previous geomorphic cycle, and that the present regime is mainly one of re-excavation. The straight courses of Cottonwood and Stubby Canyons do not reflect the positions of faults, but instead are controlled by a consistent foliation in the metamorphic rocks.

Structure. The Banning fault, the major structural feature on the north side of the pass, brings sedimentary rocks into contact with the crystalline complex throughout the 25-mile interval between Whitewater Canyon and Yucaipa Valley, and it probably extends still farther west to the San Jacinto fault zone. It is a vertical or steep reverse fault except in the area between Millard and Cottonwood Canyons, where there is a zone of low-angle thrusting. Well logs indicate that more than 5,000 feet of sedimentary rocks is present south of the Banning fault, and this, together with the very existence of San Gorgonio Pass itself, suggests large vertical displacement on the Banning fault. West of Cabazon, the Banning fault neither displaces Quaternary terraces nor appears to affect the distribution of groundwater, but Recent scarps are present near Whitewater. The Banning fault, which trends east, is more nearly parallel to major faults of the Transverse Range province than to the San Andreas system, and it is possible that the Banning fault was formerly continuous with one of the major east-west faults of the San Gabriel Mountains and has been offset along the San Jacinto fault.

The so-called San Andreas fault forms prominent scarps from San Bernardino southeast to Burro Flats, but at this point it appears to butt into the Banning fault at an angle of 45°. Between Pine Bench and Burro Flats, the San Andreas fault does not appear to separate widely differing rock types, nor is the foliation in these rocks as severely disturbed as in those along the Banning fault. The crystalline rocks have been severely deformed in the junction area of the two faults, but there is little evidence that the San Andreas fault bends so as to form a continuous break with the Banning fault. The zone of thrusting along the Banning fault evidently is related to the abutment of the two fault zones, and the Banning fault is offset in three places by faults of San Andreas trend.

The similarity of crystalline rock types on the two sides of the San Andreas fault does not seem compatible with the concept of hundreds of miles of lateral offset along this fault; even a few tens of miles of displacement is difficult to reconcile with the complex surface geometry of faults within the pass, although it must be regarded as a possibility. The Banning fault is traceable for a distance of more than 40 miles southeastward from Whitewater, and in this area it is usually referred to as the San Andreas fault. Although it probably is a result of the same over-all stress system, this fault does not appear to form a surface break that is continuous with the San Andreas fault north of San Bernardino. Certainly the San Andreas fault zone seems to fray out southeast of Canjon Pass, as pointed out by Noble (1932), and only further field work will show if any one branch truly deserves the parent name.

Acknowledgment. The field work on which the foregoing statements are based has been aided by fellowship grants from the National Science Foundation, the Standard Oil Company of California, and the California Institute of Technology.

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† Assistant Professor of Geology, University of Minnesota.

* Subsequent to drafting of the accompanying map, the strata that lie beneath the bench north of Banning have yielded vertebrate remains that suggest correlation of these rocks with the Pliocene-Pleistocene San Timoteo formation (Frick, 1921; Axelrod, 1950), rather than with the Hathaway formation of Lion Canyon.

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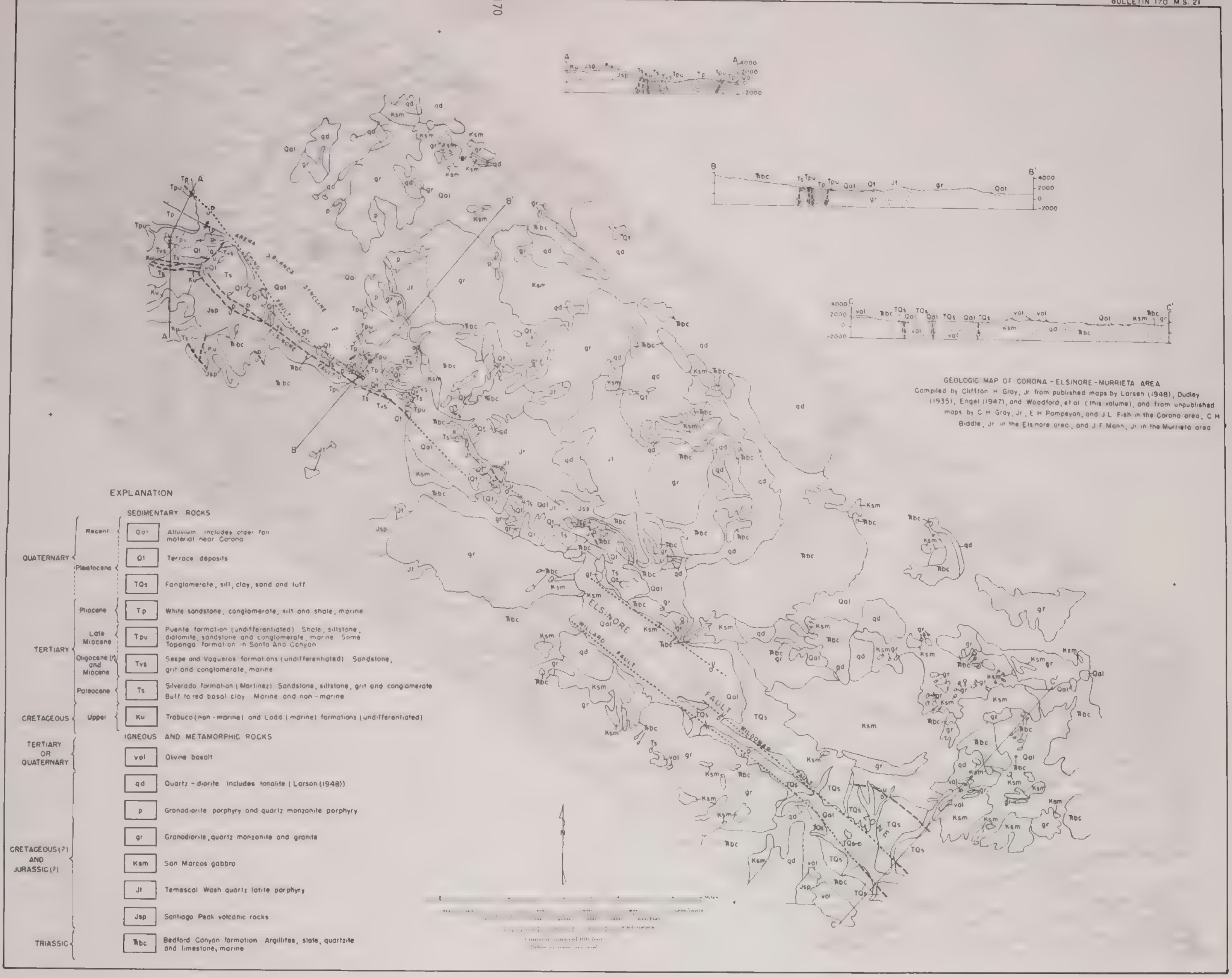

GEOLOGIC MAP OF CORONA-ELSINORE-MURRIETA AREA

Compiled by Clifton H. Gray, Jr. from published maps by Larsen (1948), Dudley (1935), Engel (1947), and Woodford, et al. (this volume), and from unpublished maps by C. H. Gray, Jr., E. H. Pampeyan, and J. L. Fish in the Corona area, C. H. Biddle, Jr. in the Elsinore area, and J. F. Mann, Jr. in the Murrieta area

EXPLANATION

			SEDIMENTARY ROCKS
QUATERNARY	Recent	Qal	Alluvium. Includes older fan material near Corona
	Pleistocene	Qt	Terrace deposits
		TQs	Fanglomerate, silt, clay, sand and tuff
TERTIARY	Pliocene	Tp	White sandstone, conglomerate, silt and shale, marine
	Late Miocene	Tpu	Puente formation (undifferentiated). Shale, siltstone, diatomite, sandstone and conglomerate, marine. Some Topanga formation in Santa Ana Canyon
	Oligocene (?) and Miocene	Tvs	Sespe and Vaqueros formations (undifferentiated). Sandstone, grit and conglomerate, marine
	Paleocene	Ts	Silverado formation (Martinez). Sandstone, siltstone, grit and conglomerate. Buff to red basal clay. Marine and non-marine
CRETACEOUS	Upper	Ku	Trabuco (non-marine) and Ladd (marine) formations (undifferentiated)
			IGNEOUS AND METAMORPHIC ROCKS
TERTIARY OR QUATERNARY		vol	Olivine basalt
CRETACEOUS (?) AND JURASSIC (?)		qd	Quartz-diorite. Includes tonalite (Larson (1948))
		p	Granodiorite porphyry and quartz monzonite porphyry
		gr	Granodiorite, quartz monzonite and granite
		Ksm	San Marcos gabbro
		Jt	Temescal Wash quartz latite porphyry
		Jsp	Santiago Peak volcanic rocks
TRIASSIC		Ћbc	Bedford Canyon formation. Argillites, slate, quartzite and limestone, marine

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 21

GEOLOGY OF THE CORONA-ELSINORE-MURRIETA AREA, RIVERSIDE COUNTY

By Clifton H. Gray, Jr.*

General Setting. The Corona-Elsinore-Murrieta map area, in southwestern Riverside County, is a strip approximately 40 miles long and 10 miles wide. The Santa Ana Mountains, one of the most rugged of the Peninsular Ranges, bound the area on the southwest and culminate in Santiago Peak, 5,680 feet high. The central part of the map area is occupied by the relatively flat-floored Elsinore-Temecula trough. Northeast of the trough are the moderately high (1,500 to 3,000 feet) Perris block, with a culmination in the Gavilan Hills north of Elsinore, and a less well defined highland mass southeast of Elsinore. In the northwest part of the area the Santa Ana River cuts through the coastal ranges and marks the geographic division between the Santa Ana Mountains and the Puente Hills.

Rock Types. The area is underlain by plutonic, metamorphic, sedimentary, and volcanic rocks that range in age from Triassic to Quaternary. Crystalline rocks are exposed at many places and evidently underlie the entire region. The oldest rocks are the Bedford Canyon slaty metasediments of Triassic age, which have been intruded by a series of late Mesozoic plutonic and dike rocks, most of which represent the southern California batholith (Larsen, 1948). In the Santa Ana Mountains, southwest of the Elsinore fault, the Bedford Canyon metasediments are unconformably overlain by the Jurassic (?) Santiago Peak volcanics, a series of mildly metamorphosed flows, tuffs and breccias.

In the Corona area, northeast of the Elsinore fault, is a rather thick sedimentary section that ranges in age from Upper Cretaceous to Quaternary; both marine and nonmarine units are present. The basal unit, the Trabuco conglomerate, is overlain by the Ladd formation, which comprises the Baker Canyon sandstone and conglomerate member and the overlying Holz shale member. The Paleocene Silverado formation rests upon the Ladd formation, and is in turn overlain by the Oligocene-Miocene Sespe formation and the lower Miocene Vaqueros sandstone and conglomerate. The middle Miocene Topanga sandstone lies upon the Vaqueros, and is overlain by the upper Miocene Puente formation, which is composed of sandstone, shale, conglomerate, and diatomite. Pliocene sandstone, conglomerate, and shale, not subdivided on the map, overlie the Puente formation.

The maximum aggregate thickness of this sedimentary section is about 17,000 feet. Resting upon it are Quaternary terrace deposits and older alluvium, with maximum thicknesses measurable in hundreds of feet, and Recent alluvium that fills the stream valleys.

Southeast of Elsinore, in the Murrieta area, the Elsinore fault zone defines several basins that occupy downfaulted blocks of a Mesozoic basement complex on which continental sediments of late Cenozoic age have been preserved. Triassic metasedimentary rocks and Jurassic (?) metavolcanic rocks of the basement complex have been intruded by younger Mesozoic plutonic rocks. Arkosic gravels were deposited upon a mature erosional surface developed on the basement rocks, and small patches of these gravels are preserved beneath olivine basalt flows of late Tertiary or Quaternary age.* The late Cenozoic continental strata can be subdivided into three units according to relative age, and consist chiefly of arkose, siltstone, and fanglomerate, with lesser amounts of tuff and diatomite. Representing late volcanic activity are nepheline basalt flows and dikes and at least one pyroclastic cone.

Structure. The most obvious structural features in the area are post-Pliocene in age. Northwest of Elsinore Lake the Elsinore system of high-angle reverse faults is dominant. Southwest of Corona the distribution and attitude of the Cretaceous and Paleocene strata show that the top of the Santa Ana Mountains marks the crest of a great northwest-trending anticline, broken slightly east of its axis by the Elsinore fault zone. The surface distribution of the Cretaceous sediments indicates a probable vertical displacement of at least 1,500 feet along the Elsinore fault southwest of Corona. Southeast of Corona the relative positions of granodiorite and volcanic rocks of the basement complex suggest a displacement of more than 5,000 feet along that portion of the Elsinore fault zone. The Arena Blanca syncline apparently extends southeastward beyond Corona, and parallels the Elsinore fault zone on its northeast side, so that in the Corona area the Elsinore trough can be regarded as a faulted syncline.

The structure southeast of Elsinore is characterized by a complex pattern of faults that have formed a series of downdropped blocks. Evidently the faults are nearly vertical (see cross section), and most of them trend northwest. Vertical displacements of several thousand feet are not improbable, whereas horizontal shifts may not have amounted to more than 1,000 feet. Structure section A-A′ shows essentially horizontal flows of olivine basalt at an altitude of about 2,000 feet on Mesa de Burro, where they are underlain by arkosic gravels that were doubtfully assigned to the Paleocene by Mann (1949) but which possibly are considerably younger. Mann reports that a similar sequence was encountered in a well a short distance east of Murrieta at a depth of about 2,450 feet, or at a point about 1,300 feet below sea level. Thus the measurable minimum vertical displacement shown between Mesa de Burro and the Murrieta graben is 3,300 feet. Northeast of Murrieta, olivine basalt similar to that on Mesa de Burro forms four small mesas standing at altitudes only about 300 feet lower than Mesa de Burro, giving good evidence for the Murrieta graben.

Geomorphology. The landforms in the area are predominantly block mountains which have been dissected marginally by streams.

Temescal Canyon, a graben-like valley that extends from Corona to Elsinore, is often referred to as the Elsinore trough or graben. Recent mapping, however, indicates that in the Corona area it is rather a broad valley eroded in weak sediments and bounded by a young fault zone on its southwest side. A true graben about half a mile wide may exist about 6 miles southeast of Corona, whence it extends southeastward to Elsinore. There the graben widens to become the Temecula-Elsinore trough.

Dudley (1936, pp. 358-378) believed that the Perris block, which is bounded on the southwest by the Temecula-Elsinore trough, had a geomorphic history briefly summarized as follows:

1. A mature surface was developed in the area of the Perris block. Drainage was at that time toward the east.
2. This old topography was partially buried by sediments, and the Perris surface was developed. This mature surface, cut on crystalline rocks and interrupted here and there by monadnocks, covers a large area in the western part of the block and lies at an altitude of about 1,700 feet.
3. Sediments accumulated over a large area, and the Gavilan peneplain, a mature surface at an altitude of about 2,100 feet, was formed.
4. Erosion exhumed the Perris surface, and the San Jacinto River then flowed across this surface and through the Santa Ana Mountains to the sea. The river thus is superimposed where it crosses monadnocks on the Perris surface.
5. The San Jacinto River was captured by Temescal Creek, a tributary of the Santa Ana River. Elsinore Lake is a temporary feature, incidental to recent faulting.

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* Junior Mining Geologist, California Division of Mines.

* Age of gravels variously stated to be Paleocene and Late Tertiary.

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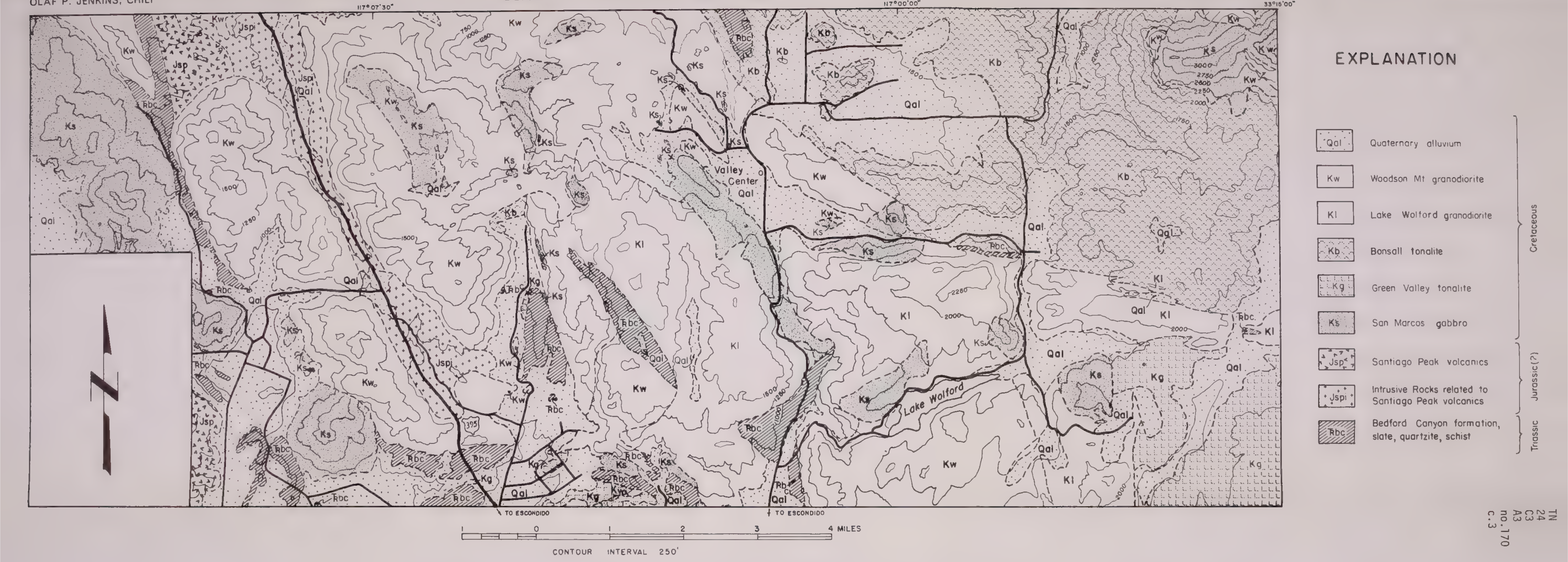
BULLETIN 170 MAP SHEET 22



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BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 22

A TYPICAL PORTION OF THE SOUTHERN CALIFORNIA BATHOLITH, SAN DIEGO COUNTY

By Richard Merriam *

The southern California batholith is a great composite mass of late Mesozoic plutonic rocks that underlies much of the Peninsular Range province. These rocks range in composition from gabbro to granite, and each of several major rock types forms numerous individual plutons whose maximum exposed dimension rarely is greater than 8 miles. The batholith as a whole is probably tonalitic in average composition. Pre-batholith rocks, most of which appear as inclusions, septa, and screens within and between masses of the plutonic rocks, are mainly metasedimentary and metavolcanic types of Paleozoic and Mesozoic age.

Exposed within the area shown on the accompanying map is a typical portion of the batholith. In some respects, however, it is far from representative, as no single map on less than a regional scale can illustrate all features of this large complex batholith or its gross relationships with the pre-batholith rocks. On the other hand, no small-scale map of a wide area can reveal the structural complexities and the details of rock distribution that exist within the batholith. Variations seem to be greater across the batholith than parallel to its length, and thus deviations from this sample area, which lies in its western exposed part, may be greater to the east than to either north or south.

The map area is least typical in terms of the relative abundance of the various plutonic rock types. As compared with the part of the batholith that has been mapped in detail, this area contains a relatively small amount of tonalite and large amounts of granodiorite and gabbro. Several types of tonalite and granodiorite that appear elsewhere are absent from this area, but none that constitute more than 3.5 percent of the known batholith are lacking. With the exception of the Lake Wolford granodiorite, all formations shown are among the most common and widespread of those exposed throughout the known batholith. Pre-batholith granite rocks, such as the Stonewall granodiorite, are common in areas farther east, but are not present here.

The map illustrates the variations in complexity of the pattern made by the numerous intrusives and masses of country rocks. Some areas are underlain by several rock types that form small bodies less than a mile in exposed length. Such areas are in contrast to others in which individual bodies several miles across are of uniform composition and only here and there are spotted with other rocks.

Although a structure map is not included here, the principal structure features are more or less outlined by the trends of the elongate masses of pre-batholith rocks and by the configuration of the intrusive units. The larger tabular bodies or screens of pre-batholith rocks in general strike northwest and dip steeply, whereas the smaller bodies show considerable variation of attitude and indicate numerous minor structural complexities. Most contacts between the batholith units and the country rock are concordant, although there are some notable exceptions. Many of the gabbro contacts, for example, are very irregular and commonly are cross-cutting. The original contacts of gabbro against older rocks may have been modified through stoping by younger plutons, which could have removed original concordant borders. Many bodies of gabbro appear to be remnants of masses that once were larger.

The tonalites and granodiorites occur chiefly as large, irregular bodies that include smaller masses of schist and gabbro. Commonly dikes or tongue-like projections extend from the plutons of granodiorite into older rocks, but this feature is not well shown in the portion of the batholith illustrated in the accompanying map.

These structural features and related evidence support the belief that emplacement was principally by stoping and in part by assimilation, with forceful injection playing a minor role.

The repeated association of certain rocks with certain others throughout the batholith is noteworthy, although it is not particularly well shown in this area. The Green Valley tonalite, for example, commonly is in contact with and is gradational into the San Marcos gabbro. An even more common association is that of schist or quartzite with granodiorite, for example the Lake Wolford granodiorite. Neither the abundance of bodies of schist in and adjacent to this formation nor the intimacy of mixing of the two rocks can be shown on a map of the scale here presented. Innumerable slivers of schist that are too small to be mapped occur in the vicinity of the larger ones shown. These relations and the locally gradational contacts between the coarse-grained, uniform Woodson Mountain granodiorite and the fine-grained, variable Lake Wolford granodiorite suggest that the latter may be at least in part the product of assimilation or replacement of older rocks.

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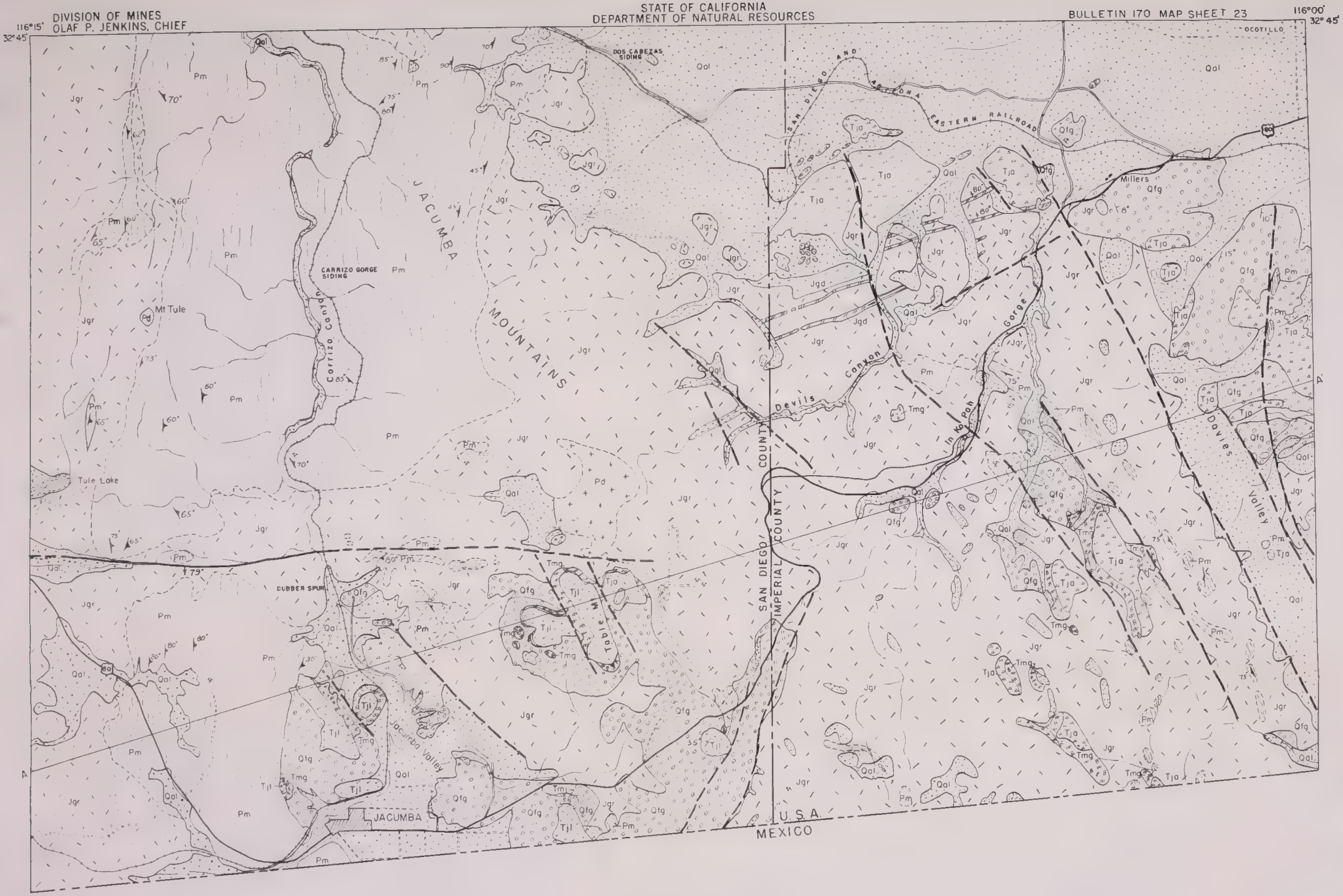
BULLETIN 170 MAP SHEET 23



LEGEND

Qal	QUATERNARY	RECENT ALLUVIUM-Alluvium of the present cycle of deposition. Coarse, arkosic sands and gravels.
Qfg		POST-LAVA FANGLOMERATE-Sands and gravels of older alluvium, now being eroded.
Tjl	TERTIARY	JACUMBA LAVA-Chiefly andesite and olivine basalt flows.
Tja		JACUMBA PYROCLASTICS-White to red tuffs, gray to red agglomerates, with some interbedded gravels. Chiefly andesitic in composition.
Tmg		TABLE MOUNTAIN GRAVELS-Well-rounded to angular fragments of local rocks and rocks similar to the Santiago Peak volcanics near the Pacific coast.
Jgd	Jurassic Cretaceous	QUARTZ DIORITE DIKES-Fine-grained biotite quartz diorite dikes Finer-grained and more melanocratic than the La Posta
Jgr		LA POSTA QUARTZ DIORITE-Quartz diorites of at least two different ages. Includes many unmapped pegmatite dikes.
Pd	Pre-Jurassic	DIORITE-Chiefly hornblende diorite. Includes unmapped quartz diorite and pegmatite dikes.
Pm		JULIAN SCHIST-Metamorphic rocks. Includes gneiss, biotite schist, marble, amphibole schist, and quartzite, with many unmapped pegmatites.

——	Contact, well located	━━	Fault, well located
------	Gradational contact	— —	Fault approximately located
8	Attitude of bedding	75	Attitude of foliation

AREAL GEOLOGY MAP OF THE JACUMBA QUADRANGLE

SAN DIEGO AND IMPERIAL COUNTIES CALIFORNIA

Field Geology Classes of San Diego State College
Edited by Baylor Brooks and Ellis Roberts

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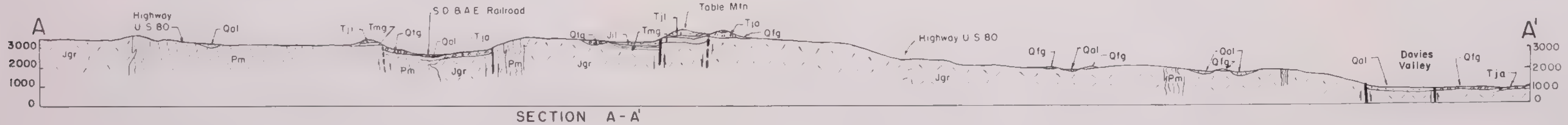

SECTION A-A'

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 23

GEOLOGY OF THE JACUMBA AREA, SAN DIEGO AND IMPERIAL COUNTIES

By Baylor Brooks* and Ellis Roberts*

GEOLOGIC FEATURES

Physiographically the Jacumba area represents the boundary between the Peninsular Ranges and the Colorado Desert. The Jacumba Basin and surrounding fault blocks, whose upper surfaces represent disconnected remnants of old erosion surfaces, lie to the west. The Imperial section of the Salton trough lies to the east. Separating the two areas is a complex fault zone in which a throw of 2,000 or 3,000 feet is absorbed among several parallel northwest-trending breaks. Remarkable cutting by Carrizo Creek because of its low outlet to the Salton Sink on the east has produced the spectacular Carrizo Gorge and will eventually destroy the Jacumba Basin.

. The oldest rocks in the area are metamorphic types that include gneiss, amphibole schist, biotite-muscovite schists, quartzite, marble, and tactite. They are best exposed in the western third of the area. Schistosity in them dips at angles of 45 degrees or more, and in general is parallel to bedding and to stratigraphic units of distinctive lithology. These metamorphic rocks probably are equivalent to the Julian schist of areas to the northwest, which is pre-Cretaceous in age and may include rocks that represent a Paleozoic-Jurassic age range.

A coarse-grained diorite with predominant amphibole is probably younger than the metamorphic rocks. The largest exposed masses of this rock are in the center of the mapped area. Both it and the metamorphic rocks have been intruded by quartz diorites. At least two periods of intrusion are evidenced by quartz diorite with pegmatite dikes, which appear as inclusions in the younger quartz diorite. The older quartz diorite shows stronger planar structures. The age of both quartz diorites is Jurassic to Cretaceous, on the basis of lithologic correlation with rocks in other areas. Dikes of fine- to medium-grained biotite quartz diorite have been intruded into the plutonic rocks in the northwestern section of the area.

Pegmatite dikes transect all of the rocks noted above. They are especially well developed on the northeastern side of Mt. Tule, and some of them are as much as 60 feet thick and half a mile long. Albite, quartz, perthite, and muscovite are the most abundant minerals, and banding is formed in many dikes by variations in both grain size and mineral composition.

Deformation and erosion preceded the deposition of the Table Mountain gravels and sands. These contain fragments of dacites and other aphanitic rocks that show strong similarities to the Jurassic (?) Santiago Peak volcanics of western San Diego County. The gravels are partially interbedded with and principally overlain by other volcanic rocks. These younger volcanic rocks are chiefly andesitic in composition, and consist of a lower pyroclastic member and an upper lava member. They are probably of Miocene or Pliocene age, on the basis of lithologic correlation with volcanic rocks in the Coyote Mountains to the east.

After the volcanic activity had ceased, uplift and block faulting created much of the present topography and established the conditions for the accumulation of fanglomerates, most of which have been well dissected by the present cycle of erosion. Modern alluvium is being deposited along the present drainage channels.

INTERESTING MINERAL OCCURRENCES

Andalusite. 0.8 mile southeast of Bankhead Springs. Pink divergent crystals in pegmatite.

Asbestos. 4 miles north of Jacumba. Tremolite with vermiculite and chlorite.

Beryl. On northeast slope of Mt. Tule. Green crystals up to 3 cm. in diameter in pegmatite.

Clinozoisite. At many localities. Best is 2 miles N. 60° E. of Mountain Springs, where gray to green crystals as much as 10 cm. long occur in contact-metamorphic zones near marble with garnet, quartz, etc.

Rhodonite. 2.3 miles northwest of Jacumba, in contact-metamorphic zone with quartz and manganese oxides.

Scheelite. 500 feet east of San Diego and Arizona Eastern Railroad and 2.2 miles north of Dubber spur. In contact-metamorphic zone in marble.

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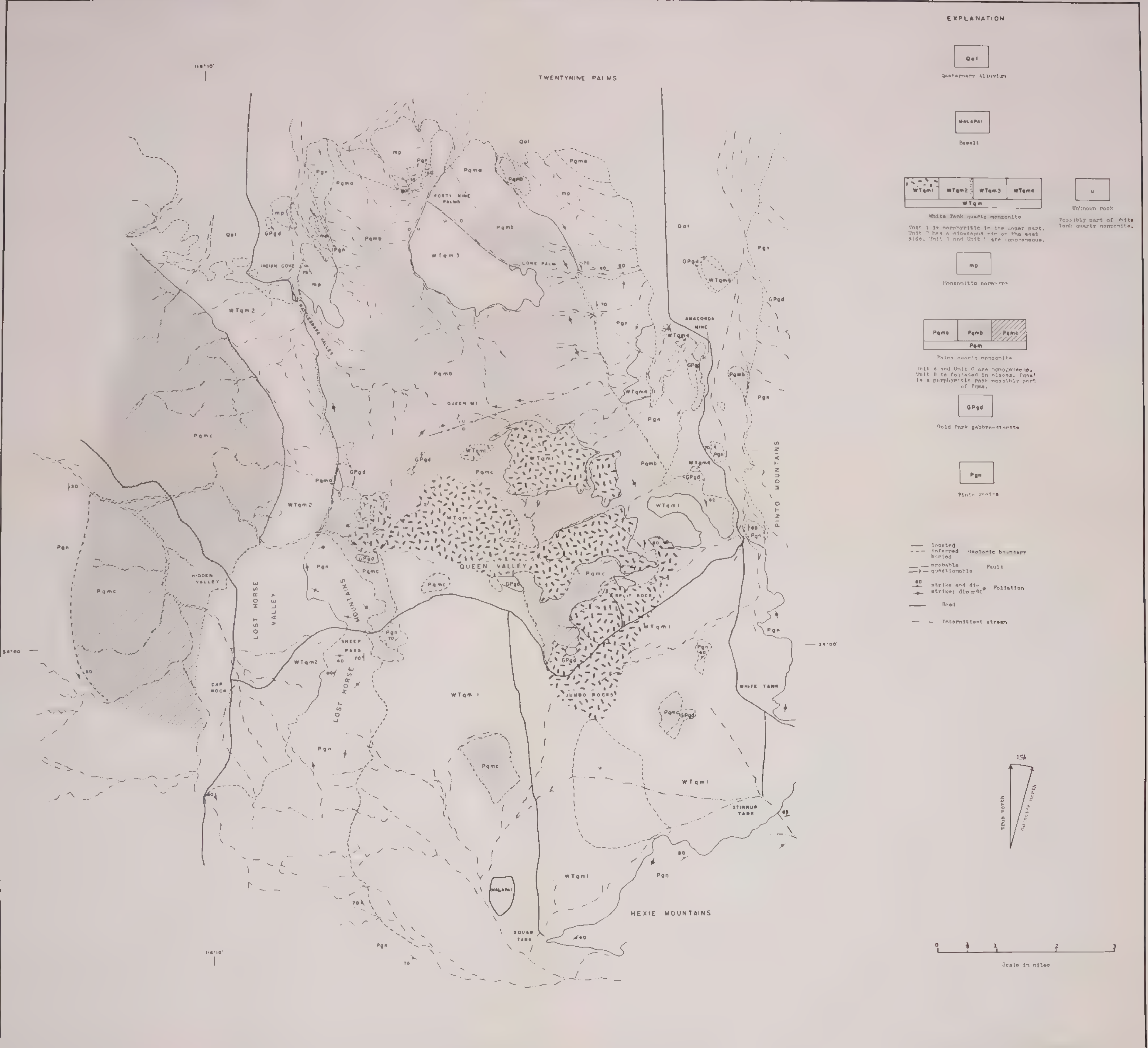

GEOLOGIC MAP OF A PORTION OF JOSHUA TREE NATIONAL MONUMENT

Geology by John J. W. Rogers, 1953-1954. (In part adapted from W. J. Miller, 1938.)

Planimetric base by John J. W. Rogers from aerial photographs obtained from U. S. Air Force.

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BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 24

GEOLOGY OF A PORTION OF JOSHUA TREE NATIONAL MONUMENT, RIVERSIDE COUNTY *

By John J. W. Rogers †

The area shown on the accompanying geologic map consists entirely of crystalline rocks of uncertain to unknown age. The major types present are a gneiss and a series of plutonic rocks.

The oldest formation in the area is the Pinto gneiss, a middle-rank metamorphic rock that is characterized by well-developed foliation and a mineral assemblage of quartz, plagioclase, biotite, and scattered muscovite, hornblende, and potash feldspar. The trend of the foliation is generally north to northwest, and the dip is highly irregular but commonly very steep to vertical. A high content of quartz (50 percent or more) and the presence of layers, 100 to 500 feet thick, of contrasting composition indicate that the gneiss is largely of metasedimentary or metavolcanic origin. In places this rock is intimately mixed with granitic material and appears to grade into the Palms quartz monzonite, but in most places the contact between the quartz monzonite and the gneiss can be located within 10 feet.

The Gold Park gabbro-diorite occurs in small, isolated masses scattered through both the gneiss and the Palms quartz monzonite. It is a fine- to coarse-grained rock consisting primarily of hornblende and plagioclase in the andesine range; parts of the rock also contain olivine, biotite, and possibly pyroxene. Its age relative to the Pinto gneiss cannot be definitely determined, but it probably was intruded into the gneiss or into the sediments from which the gneiss was derived.

The Palms quartz monzonite is intrusive into the Pinto gneiss, but its age with respect to the gabbro-diorite is uncertain. Relatively abrupt contacts, in some places gradational over distances of less than one inch, with the gneiss, as well as the occurrence of swarms of quartz monzonite dikes that cut the gneissic foliation in many places, indicate that the quartz monzonite was formed largely by crystallization of a melt. This igneous rock has been separated into three units. Unit A is coarse to medium grained, inequigranular, and seriate, and consists of approximately equal amounts of quartz, potash feldspar, and plagioclase (An_{25}), scattered biotite and hornblende, and a characteristic assemblage of sphene, magnetite, apatite, and members of the epidote group. Unit B is finer grained, contains less dark minerals, and has a more sodic plagioclase (An_{10}) than Unit A, and Unit C is fine grained, roughly equigranular, and has the same general mineralogic composition as Unit B. Units A and B are characterized microscopically by very complex textural relations between potash feldspar and plagioclase. Borders between the two minerals are very irregular and are marked by islands of each mineral in the other, myrmekite is abundant in irregular grains of albite around the borders of the potash feldspar, and both perthite and antiperthite are present. Parts of Unit B are foliated, but Units A and C are generally massive.

A monzonitic porphyry grades into the Palms quartz monzonite in some places, into the Pinto gneiss in others, and has abrupt contacts against these rocks in still other places. About 30 percent of the porphyry consists of pink, highly poikilitic, subhedral crystals of potash feldspar, some of which are as much as 6 inches long. Slightly smaller and non-poikilitic phenocrysts of plagioclase are about as abundant as the potash feldspar. The other major constituents are quartz and either greenish hornblende, greenish-brown biotite, or (rarely) both of these minerals. The accessory minerals are identical with those of the Palms quartz monzonite. The groundmass of the porphyry generally forms about 10 percent of the rock, and consists of fine-grained, highly intergrown potash feldspar, plagioclase, and quartz in various proportions.

In many of the gradations into gneiss, it is apparent that at least part of the monzonitic porphyry was formed by incorporation of the gneiss in a medium capable of developing large crystals of both potash and plagioclase feldspars. The general peripheral distribution of monzonitic porphyry around the Palms quartz monzonite and the gradations into the quartz monzonite suggest that the porphyry was formed by reaction between quartz monzonite and gneiss. This reaction must have involved addition of potash and soda to the gneiss. Most parts of the monzonitic porphyry are massive, but in places a definite planar structure is present, and commonly is parallel to the contact with the adjacent rocks. Along some of these contacts structural and textural evidence indicates that the porphyry was sufficiently mobile to undergo movement.

The White Tank quartz monzonite is the youngest plutonic rock in the area. Contacts with wall rocks invariably are abrupt, and commonly are marked by zones of relatively fine-grained quartz monzonite and by small pegmatitic vugs. The rock has been subdivided into four units, two of which contain two facies. In general, however, it can be described as a well-jointed, coarse- to medium-grained, inequigranular quartz monzonite that contains roughly equal amounts of quartz, potash feldspar, and oligoclase. A few percent of biotite is present in most places, but ordinarily mafic and accessory minerals are uncommon.

Unit 1 of the White Tank quartz monzonite exhibits a vertical variation over a range of 1,000 feet from equigranular granodiorite at the base to inequigranular quartz monzonite at the top; there are upward increases in the percentage and grain size of potash feldspar and the Ab/An ratio of the plagioclase, and a decrease in the amount of mafic minerals. Unit 2 is inequigranular quartz monzonite that apparently is homogeneous over the same vertical range as that just noted for Unit 1. Along a part of the eastern contact, Unit 2 contains 1 to 2 percent of muscovite and rare spessartite. Unit 3 is similar to the micaceous rim of Unit 2; it contains 5 percent of muscovite, scattered red garnet, and laths of primary plagioclase with a composition of nearly pure albite (An_{05} or less). Unit 4 is similar to the upper facies of Unit 1 in its content of large crystals of potash feldspar, but it differs from Unit 1 in containing approximately 25 percent of groundmass material in which all the major minerals are represented.

A rock designated in the map legend as "unknown rock" is a fine-grained granodiorite whose temporal and genetic relations to other formations in the area are not known. It is similar in composition to the more basic parts of the White Tank quartz monzonite, and may represent a younger, more rapidly cooled injection of the material that formed the large masses of quartz monzonite. The White Tank quartz monzonite is believed to have been formed by crystallization and differentiation of an intruded melt.

In addition to the major plutonic rocks, several minor igneous rocks are present. The White Tank quartz monzonite is cut by dikes and irregular small masses of aplite, pegmatite, and basic rocks. In places the Palms quartz monzonite and the monzonitic porphyry contain abundant silicic and basic dikes that are about 6 inches in average width. Presumably the youngest igneous rock in the area is the olivine-bearing basalt that makes up the Malapai volcanic plug.

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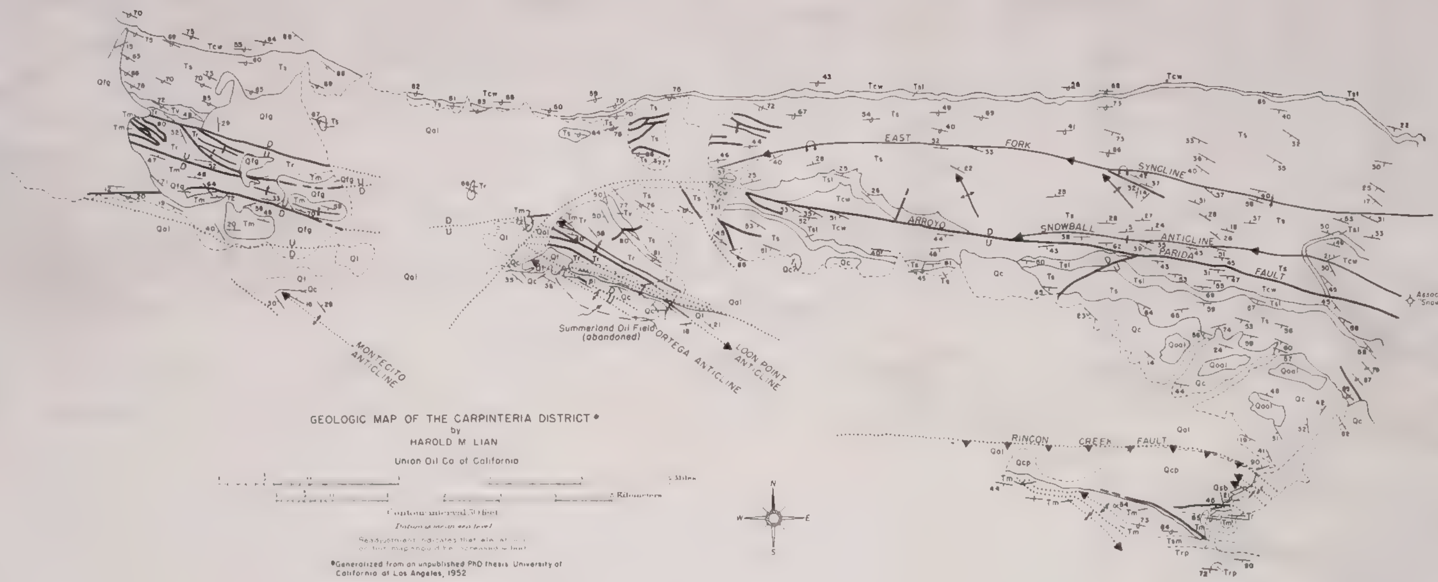

GEOLOGIC MAP OF THE CARPINTERIA DISTRICT*
by
HAROLD M LIAN
Union Oil Co of California

*Generalized from an unpublished PhD thesis University of California at Los Angeles, 1952

DIVISION OF MINES
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GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 25

GEOLOGY OF THE CARPINTERIA DISTRICT, SANTA BARBARA COUNTY

By Harold M. Lian *

INTRODUCTION

The area shown on the accompanying geologic map and referred to as the Carpinteria district is the lowland region that extends from the foothills of the Santa Ynez Mountains southward to the ocean and from the city of Santa Barbara eastward to Rincon Creek

The gross structure of the Santa Ynez Mountains is anticlinal, and this large fold is ruptured in its axial region by the Santa Ynez fault and several smaller breaks. The steeply dipping sandstone beds visible from U. S. Highway 101 form a part of the south limb of the fold. The beds normally dip south but are overturned to the north in western Ventura County and north of the city of Santa Barbara, where the terms Matilija overturn and Montecito overturn have been applied to the respective structures.

The oldest rocks in the structurally complex axial part of the Santa Ynez fold, which lies north of the crest of the range, are sedimentary strata and serpentine of the Jurassic (?) Franciscan group. Cretaceous strata crop out in the center of the range, on the south flank of the fold, and in general successively younger formations crop out southward from the crest of the range to the ocean.

STRATIGRAPHY

The Jurassic (?), Cretaceous, and Eocene formations older than the Coldwater sandstone do not crop out in the area covered by the accompanying geologic map, but they presumably are present in the subsurface of the Carpinteria district. The accompanying stratigraphic column lists pertinent data for the surface and subsurface formations, and the exposed formations are described briefly below.

Coldwater Sandstone. The light gray to grayish yellow, well-indurated marine Coldwater sandstone was deposited in a regressing upper Eocene sea. Bedding ranges from a few feet to tens of feet in thickness, and the sandstones, although typically coarse-grained arkoses, are remarkably varied in detail. Thin interbeds of silty shale contain a sparse foraminiferal fauna. Megafossils are largely restricted to oysters. The formation probably is wholly of shallow-water origin, and is conformably overlain by the nonmarine Sespe formation.

Sespe Formation. The nonmarine Sespe formation is a thick sequence of variegated clastic strata. The characteristic color is grayish red, but many thin beds of sandstone and siltstone show varying hues of yellow and green, especially in the upper part of the formation. In general the lower half of the formation is thick-bedded sandstone and conglomerate, and the upper half is soft, thin-bedded sandstone, siltstone, and shale. The beds of conglomerate contain abundant clasts of Franciscan rocks. These beds are more numerous and range higher stratigraphically in the eastern part of the area than in the western part, where they occur only near the base of the formation.

A distinctive unit that constitutes the basal 225 to 450 feet of the Sespe formation between Toro Canyon and Rincon Creek is referred to as the lower member. This is a grayish pink, massive, cross-stratified, very coarse-grained to pebbly sandstone.

Numerous samples of Sespe sandstone have been analyzed for grain-size distribution, and the results consistently have revealed a sandstone as well sorted as either the underlying marine Coldwater sandstone or the overlying marine Vaqueros sandstone. The degree of sorting, regularity of bedding, presence of cut-and-fill structures, and the existence of delicate laminations within beds indicate a deposit laid down by water, possibly in a large lake or on a large floodplain.

The Sespe formation ranges in age from late Eocene to early Miocene in the Ventura basin, but no fossils have been reported from the section in the Carpinteria district. It rests conformably on the upper Eocene Coldwater sandstone, and is separated from the overlying lower Miocene Vaqueros sandstone by a disconformity or possibly by a slight angular unconformity. In this area, therefore, it is believed to span the Oligocene epoch.

Vaqueros Sandstone. The marine Vaqueros sandstone represents the basal deposit of a transgressing sea that occupied the Carpinteria district continuously during Miocene and a part of Pliocene time. A thin basal conglomerate is present locally, and lenses of conglomerate and coarse beds of sandstone occur throughout the lower 50 feet of the formation. The upper part of the formation is massive, fine-grained sandstone and siltstone.

The Vaqueros formation contains the coarsest Miocene sediments in the Carpinteria district. They grade upward into massive siltstone and claystone of the Rincon formation, which in turn grade into the siliceous shales of the Monterey formation.

Rincon Formation. The Rincon mudstone is locally divisible into a lower massive siltstone member, a middle claystone and clay shale member, and an upper tuffaceous siltstone member. The lower member is soft, dark gray, and weathers subconchoidally. The middle member consists of claystone with at least two prominent horizons of slightly siliceous clay shale. Calcareous concretions are abundant, and also occur in the other members of the formation. The relatively unconsolidated vitric tuffs in the upper member form beds 1 foot to 10 feet thick. Glass shards are a conspicuous constituent of the associated siltstone.

The glass in the tuffs is exceptionally fresh and has an index of refraction of 1.496 ± .001. This value was constant in 14 samples collected from various tuff beds in the upper member at Santa Barbara and Summerland. The same figure has been reported for glass in the Obispo tuff of San Luis Obispo County (Bramlette, 1946), which probably correlates with one of the tuff beds in the upper Rincon of the Carpinteria district. Pyroclastic deposits in the Rincon may be genetically related to the Tranquillon volcanics of the Point Arguello area (Dibblee, 1950).

Monterey Shale. The Monterey shale is characterized by the presence of siliceous rocks—impure diatomaceous shale, porcelaneous shale, and chert—and includes phosphatic shale, limestone, clastic shale, and pyroclastic material.

The Monterey shale at Rincon Point is divisible into three members. The lower member consists chiefly of laminated silty and calcareous shale. A 10-foot bed of bentonite is present near the base, and phosphatic shale occurs within the upper part. The middle member is characterized by the presence of thin-bedded, laminated, argillaceous limestone and chert. Other sediments include phosphatic shale and dark brown silty shale. The upper member consists of thin-bedded clastic shale and impure diatomaceous shale. These are dark brown to black on fresh exposures, but weather to light gray.

A different facies is represented at Santa Barbara and Montecito, where the Monterey consists mainly of diatomaceous and porcelaneous shale with a minor amount of thin-bedded chert. The entire formation is not present; the part of the section corresponding to the lower member at Rincon Point has been cut out by faulting, and only parts of the interval correlative with the middle member are exposed.

Santa Margarita Formation. The laminated silty shales of the Monterey formation grade upward abruptly into a mudstone formation 750 to 800 feet thick. This is the youngest Miocene unit in the Carpinteria district, and crops out only at Rincon Point, where it is exposed along the railroad tracks beneath the underpass. It is mainly massive mudstone and clayey siltstone, and 65 feet of laminated silty shale is present about 235 feet above the base of the formation. Fresh surfaces are dark gray with a slight greenish cast. The color on weathered surfaces varies among yellowish gray, light olive-gray, pale olive, and pale greenish yellow. The mudstone weathers into fragments with subconchoidal fracture, not unlike the Rincon mudstone. Well preserved Foraminifera are extremely rare, in contrast to their great abundance in the Rincon formation and Monterey shale. Sponge spicules and Radiolaria are common.

Repetto Formation. The Repetto siltstone, of early Pliocene age, is exposed at a few places along the shore line, and offshore exposures can be seen during periods of low tide. About 600 feet of section is incompletely exposed at Rincon Point. The contact with the underlying Santa Margarita formation is concealed, but the accordance of attitudes and the lithologic similarity of the two units suggest a conformable relationship.

The Repetto is a massive, concretionary siltstone that ranges in color from light olive-gray to gray with a greenish cast. It is coarser than the mudstone of the Santa Margarita. Glauconite is abundant, and well-preserved Foraminifera occur throughout the exposed section.

Santa Barbara Formation. The Santa Barbara formation unconformably overlies the Miocene and lower Pliocene beds. Oil-stained conglomerate and fossiliferous sandstone occur at the base, above which is a section of soft, rather massive sandstone and siltstone. The formation grades upward and laterally into the nonmarine Casitas formation.

The lower part of the Santa Barbara has been assigned to the uppermost Pliocene by some workers (Bailey, 1943), whereas others consider the entire formation to be Pleistocene (Woodring, 1952).

Casitas Formation. The Casitas formation is a tough, yellowish brown, clayey to pebbly sandstone and cobble-boulder conglomerate. It is crudely stratified and the beds are lenticular. Most of the clasts have been derived from the Sespe and older formations exposed in the Santa Ynez Mountains.

Upper Pleistocene Deposits. Upper Pleistocene sediments are confined to fanglomerates and marine terrace deposits, and with the exception of the Carpinteria formation they are as yet unnamed. These deposits are of interest chiefly because of the very late Pleistocene or Recent deformation that they record.

The Carpinteria formation is a thin, tilted terrace deposit of weakly consolidated sandstone and conglomerate that lies unconformably upon Miocene and lower Pleistocene formations between Rincon Point and Carpinteria. In the vicinity of Carpinteria the unconsolidated sands have been saturated with heavy oil exuding from the Monterey shale. Before the turn of the century the asphaltic sand was quarried, and the oil was extracted from it and shipped by boat to San Francisco and other ports for use as paving material.

Abundant remains of plants and vertebrates are preserved in this formation at the old asphalt quarry near the southeast corner of the town of Carpinteria. The deposit occurs in sands and gravels that grade downward into basal fossiliferous marine sands, and is especially significant because it contains nearly contemporaneous invertebrate, vertebrate, and floral remains.

STRUCTURE

The recency of diastrophism in the Carpinteria district has resulted in close agreement between structure and present topography. The thick beds of sandstone in the Eocene section have behaved competently during the folding, and now form a homocline on the south flank of the Santa Ynez Mountains. The incompetent mudstones and shales of the Miocene formations, on the other hand, have been extensively broken and intricately folded.

Folds. The Snowball anticline and the East Fork syncline are large, open folds except north of Carpinteria, where the syncline is tightly compressed and its north limb is overturned. These folds impinge against or are truncated by the Arroyo Parida fault. Numerous small folds are present in the Miocene formations at Santa Barbara, Montecito, Summerland, and Carpinteria.

Faults. The Arroyo Parida fault is the most prominent break within the map area. It can be traced for a distance of approximately 15 miles, and appears to dip north at angles of 65 to 80 degrees. It apparently is a normal fault, although its subsurface configuration is not known. The dip-slip component of movement is approximately 2,500 to 3,000 feet.

The Rincon Creek thrust fault is exposed on the west bank of Rincon Creek. It has been penetrated by several wells drilled on the Carpinteria Plain, and has a south dip of 50 to 70 degrees.

The hills of the Riviera district, in the northern part of Santa Barbara, are bordered by high-angle faults. The Mesa, southwest of Santa Barbara, has been uplifted along a fault that bounds it on the north. The city of Santa Barbara occupies the structural depression between these relatively uplifted fault blocks.

GEOLOGIC HISTORY

The Carpinteria area was submerged during a large part of Cretaceous and Tertiary time. The pre-Tertiary history is not known in detail, but from 15,000 feet to possibly 26,000 feet of Cretaceous strata are present in the San Rafael and Santa Ynez Mountains to the north, and several thousand feet of similar strata have been reported from some of the Channel Islands. These thicknesses represent geosynclinal deposition, and it is probable that thousands of feet of Cretaceous beds are present in the subsurface of the Carpinteria district.

Diastrophism between late Cretaceous and Tertiary time is recorded from the San Rafael Mountains (Reed and Hollister, 1936) and the Santa Ynez Mountains (Page, et al., 1951). The area again was submerged by middle Eocene time and, except during the Oligocene, when the nonmarine Sespe beds were deposited, marine sediments accumulated without interruption until middle or late Pliocene time.

Uplift and folding occurred between middle Pliocene and early Pleistocene time (or within late Pliocene time, depending upon the age assigned to the Santa Barbara formation). Marine waters then invaded the Carpinteria district for the last time, and the upper Pliocene and/or lower Pleistocene Santa Barbara formation was deposited.

An orogeny that probably culminated in mid-Pleistocene time elevated the Santa Ynez Mountains, folded and faulted the Santa Barbara and older formations, and produced the major structural features of the area.

The unconformity between the lower Pleistocene Casitas formation and the upper Pleistocene fanglomerates and terrace deposits can be seen at Summerland, along the beach below Ortega Hill, where a maximum angular discordance of 75 degrees is exposed.

Late Pleistocene deformation has produced faults and folds in the terrace deposits and fanglomerates. The fanglomerate at Santa Barbara and Montecito is in fault contact with the Rincon mudstone and the Monterey shale, and has been locally overturned. Upper Pleistocene fans at Loon Point have been sharply folded into the Loon Point anticline. This fold is cut by a younger northeast-trending thrust fault, which has displaced the base of the oldest fan at least 400 feet. There is evidence that the fold was growing while the fans were being deposited. This diastrophic activity is very late Pleistocene in age, and it may have continued during Recent time.

The area between Summerland and Rincon Point appears to be subsiding at the present time. Large creeks flowing onto the Carpinteria Plain have no fans. They are literally drowned in debris, whereas creeks of comparable size and drainage area at Montecito and Santa Barbara have well-developed alluvial fans. The presence of the *estero* at Carpinteria also suggests a subsiding area.

ECONOMIC FEATURES

Oil wells were drilled at Summerland as early as 1877 (Arnold, 1908), and activities in the field reached a peak about 1900, when there were 305 producing wells in the town of Summerland, along the beach, and on wharves extending a quarter of a mile into the ocean. The wells were only a few hundred feet deep, and production was from the Casitas formation and possibly in part from beds in the Santa Barbara formation. Production declined after 1902, and the field has long been abandoned.

A flurry of drilling for Vaqueros oil production took place in the late 1920's, and several new wells were completed at Summerland. A few of these are still producing. The most recent success was enjoyed by the Standard Oil Company of California when gas production was obtained from the Sespe formation in 1948 and 1949.

Numerous oil seeps in the Monterey formation are present along the beach between Carpinteria and Rincon Point. Several wells have been drilled in this structurally complicated area, but without success. Active oil seeps occur along several of the large creeks north of Summerland and Carpinteria, where the oil is coming from sandstone beds in the Coldwater formation and from the top of the Matilija sandstone. It may have originated in the Cozy Dell shale.

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STRATIGRAPHIC SECTION

Carpinteria district
(no scale)

		Stage	Formation	Map symbol	Remarks
PLEISTOCENE	Upper		Alluvium	Qal	Present cycle alluvium.
				Qoal	Old alluvium present on elevated surfaces.
				Qfg	Dissected and faulted fanglomerate
			Carpinteria	Qcp	Terrace gravels and sandstone; in part marine.
				Qt	Undifferentiated terrace deposits
UNCOMFORMITY					
	Lower		Casitas	Qc	Terrestrial gravel, sandstone and claystone, 2 000-3,000; in part the nonmarine equivalent of the Santa Barbara formation
			Santa Barbara	Qsb	Marine sandstone, siltstone and mudstone, 1,500
UNCOMFORMITY					
PLIOCENE			Repetto *	Trp	Marine, greenish gray siltstone, 600'
MIOCENE		Delmontian	Santa Margarita *	Tsm	Marine, light brown to greenish gray silty claystone and silty shale, radiolaria and spicules abundant, 750'
		? ? Mohnian Luisian Relizian	Monterey	Tm	Marine, porcelaneous, diatomaceous, calcareous phosphatic and silty shale with chert and tuff, bentonite at or near base, very foraminiferal; 1,450'
		Saucesian Zemorrian	Rincon	Tr	Marine, conchoidally weathering, concretionary mudstone and clay shale, tuff beds and tuffaceous siltstone in upper part, very foraminiferal, 2,100
			Vaqueros	Tv	Marine, light yellowish brown to olive gray sandstone and siltstone, oil sand at Summerland
LOCAL UNCONFORMITY					
OLIGOCENE(?)			Sespe	Ts	Nonmarine, variegated conglomerate, sandstone, and shale; predominantly reddish gray, 3,125'-5,000'; a pinkish gray, massive, cross-stratified sandstone is present at the base (Tsl)
DISCOMFORMITY					
EOCENE	Upper		Coldwater	Tcw	Marine light gray, indurated arkosic sandstone, 2,100'-2,500'.

* Name in local use.

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* Geologist, Union Oil Company of California, Los Angeles

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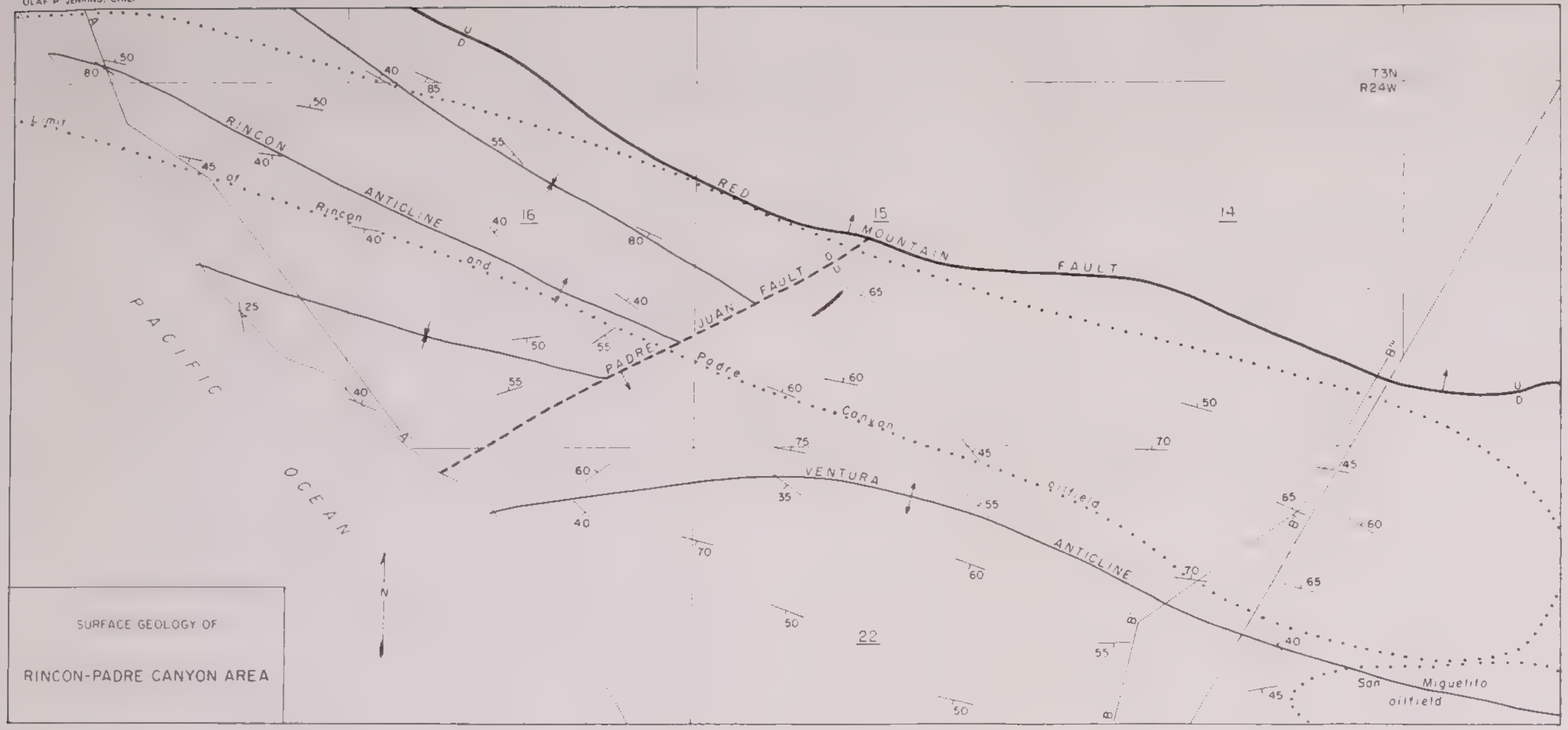
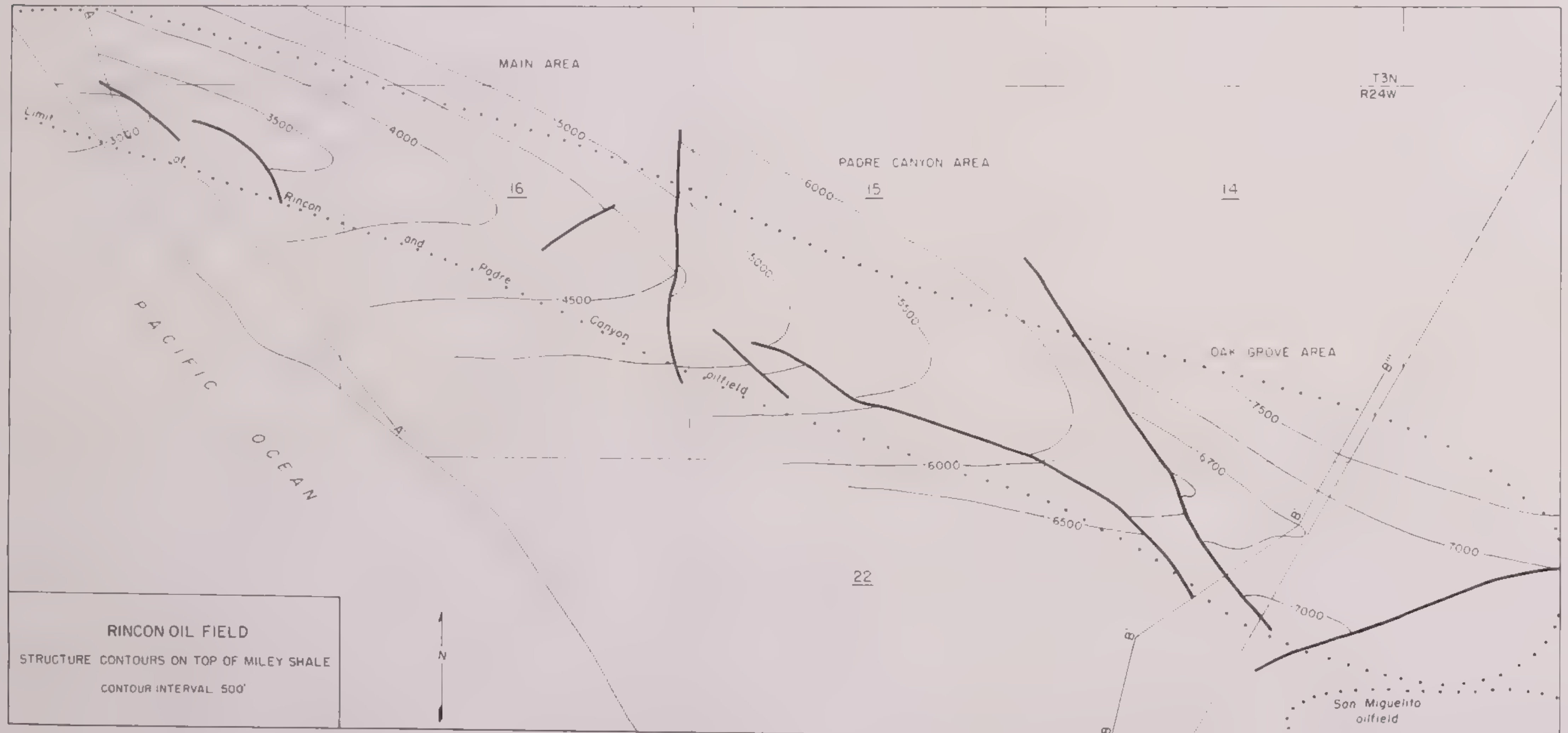
BULLETIN 170 M.S. 26



SURFACE GEOLOGY OF

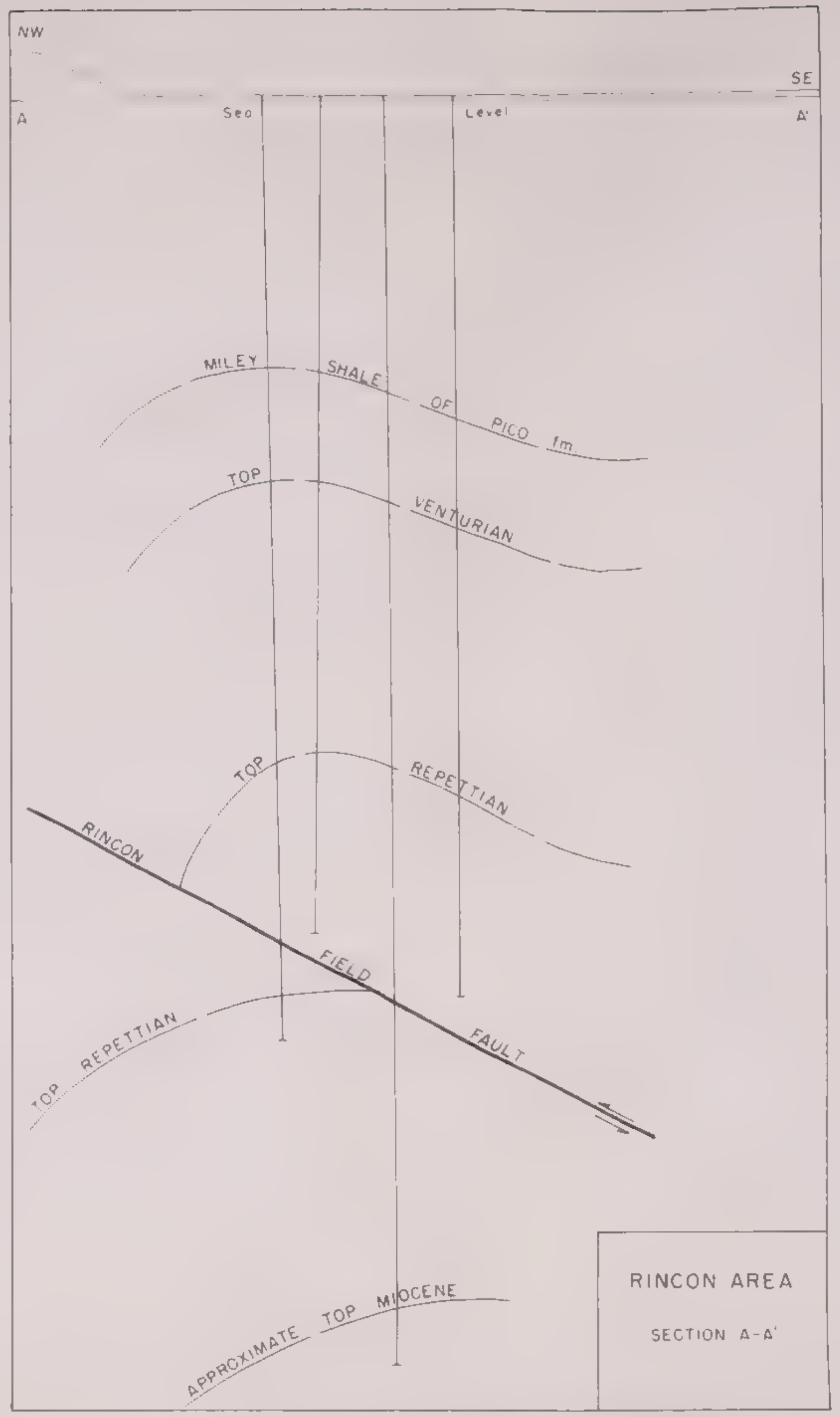
RINCON-PADRE CANYON AREA



RINCON OIL FIELD

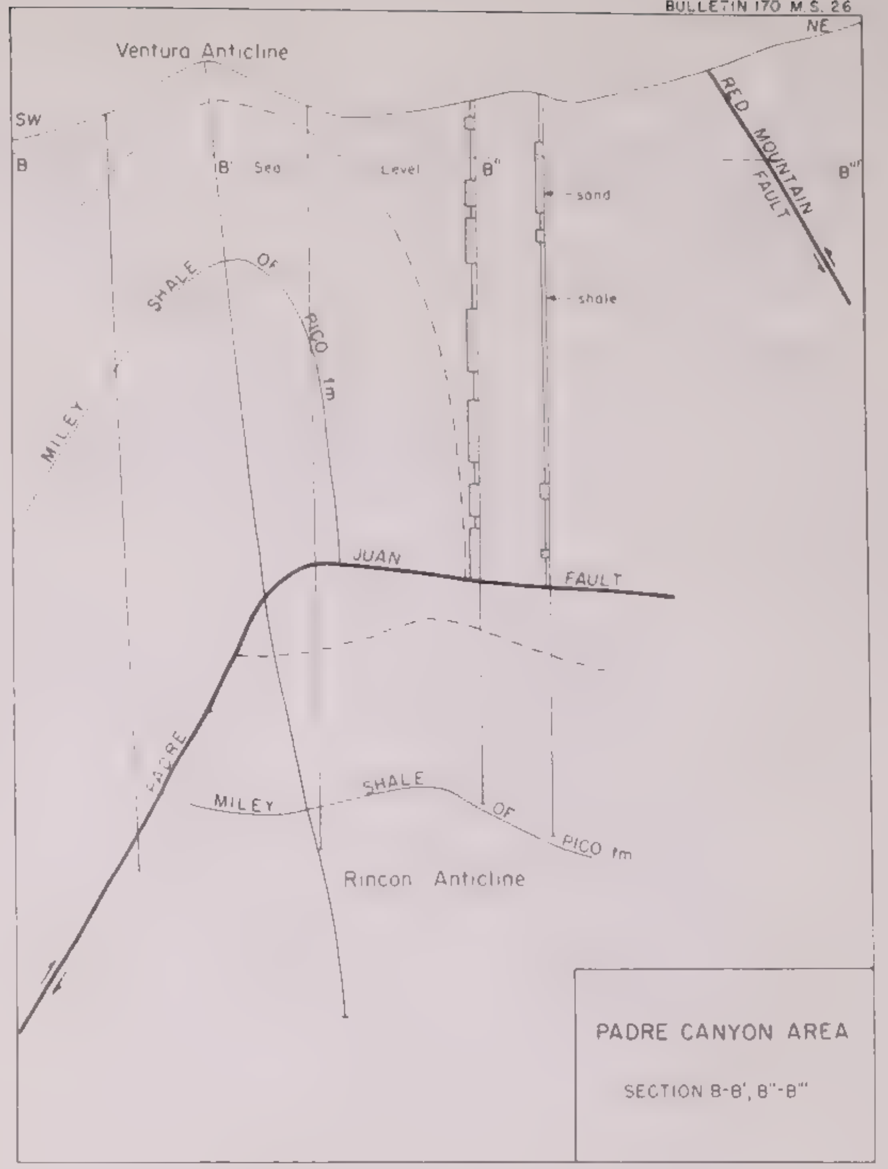
STRUCTURE CONTOURS ON TOP OF MILEY SHALE

CONTOUR INTERVAL 500'



RINCON AREA

SECTION A-A'



PADRE CANYON AREA

SECTION B-B', B''-B'''

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 26

GEOLOGY OF THE RINCON OIL FIELD, VENTURA COUNTY

By Robert H. Paschall *

The Rincon oil field lies on the southeastward plunging Rincon anticline, about 9 miles northwest of Ventura. The western, or Main area of production rises structurally in a seaward direction, and the nature of its western closure is not known. A central pool, in what is known as the Padre Canyon area, is closed up-plunge by a complex reverse cross-fault system in the vicinity of Javon Canyon. The western closure in the eastern, or Oak Grove area is effected by the east-dipping Oak Grove normal cross-fault. The history of field development and the production practices in this field are outlined in the references cited below.

The Pico formation constitutes all of the outcropping and productive rocks of the field. This unit is Pliocene in age, and here is about 11,000 feet thick. It is a monotonous series of soft to firm, medium- to coarse-grained feldspathic sands and local conglomerates, with interbedded thin but persistent gray and gray-brown clay shales. The upper part, approximately 4,700 feet thick, is assignable to M. L. Natland's Wheelerian stage (*Pulvinulinella pacifica* and *Uvigerina peregrina*), the middle 2,700 feet to the Venturian stage (*Bulmina subacuminata*), and the lower 3,600 feet to the Repettian stage (*Nonion pompilioides* and *Plectofrondicularia californica*).

A notable feature of the Pico formation in this area is the lateral persistence of individual sands and shales. Electric-log correlations can be made with little difficulty throughout the field, and permit a relatively ready solution of its complicated fault pattern. The persistence of the lithologic units indicates that structural trapping is the primary reason for the local accumulations of oil.

Almost all of the past oil production, and ninety percent of current production in the Rincon field have been derived from sands in the lower 2,500 feet of the Wheelerian-stage beds in the Pico formation. No commercial oil has been obtained from beds of Venturian age. The remainder of the production is obtained from low-permeability Repettian sands, in intervals ranging from about 700 to 2,400 feet below the top of strata representing that stage. One well in the Main Area penetrated about 600 feet of Delmontian-stage upper Miocene beds, but no production was obtained from this part of the section.

Comparison of the surface and subsurface geologic maps reveals two interesting structural anomalies:

1—A surface syncline in the Main area locally overlies the subsurface anticlinal axis. This results from the marked northward inclination of the syncline's axial plane.

2—East of the surface trace of the Padre Juan fault, the Rincon anticline underlies that fault. The fault surface is locally folded, and the axis of this fold plunges southeastward in a manner similar to that of the Rincon anticline. As a result, the parts of the Rincon anticline beneath the Padre Canyon and Oak Grove areas underlie the north flank of the overriding Ventura anticline, which is the producing structure of the San Miguelito oilfield to the southeast.

Cross-section B-B′-B″-B‴ indicates the great variations in throw that can be encountered in a short lateral distance, where folded rocks are displaced by a folded fault.

Cross-section A-A′ depicts the Rincon field fault, informally known as the "C-3 fault." It is present only in the subsurface, strikes northeast, and dips to the south. It has a reverse throw of about 2,500 feet.

Parallel to the Rincon field on the north is the great north-dipping Red Mountain thrust fault, which has a throw of about 15,000 feet in the vicinity of the field. In all likelihood, the Rincon field fault and the Padre Juan fault butt into the Red Mountain fault zone. It is interesting to note that, although minor faults have controlled oil-pool segregation along the Rincon anticline, none of the three major faults appears to have had a critical effect on oil accumulation.

As shown on the subsurface map, certain structure contours in the Main and Padre Canyon areas continue unbroken outside the limits of oil accumulation. Commercial petroleum is confined to the axial region of the fold, but extends a little farther down the north flank than it does down the south flank. Also, the oil-water contact in both the Miley (Wheelerian-age) and C-3 (Repettian-age) zones is found at progressively lower levels as traced eastward in the general direction of plunge of the anticline.

The Rincon oilfield thus possesses these two distinctive features:

1—A marked degree of independence of its oil zones from structural control.

2—An easterly tilt of the oil-water contact in each major oil zone.

Both of these features indicate that the field provides an example of hydrodynamic oil entrapment.

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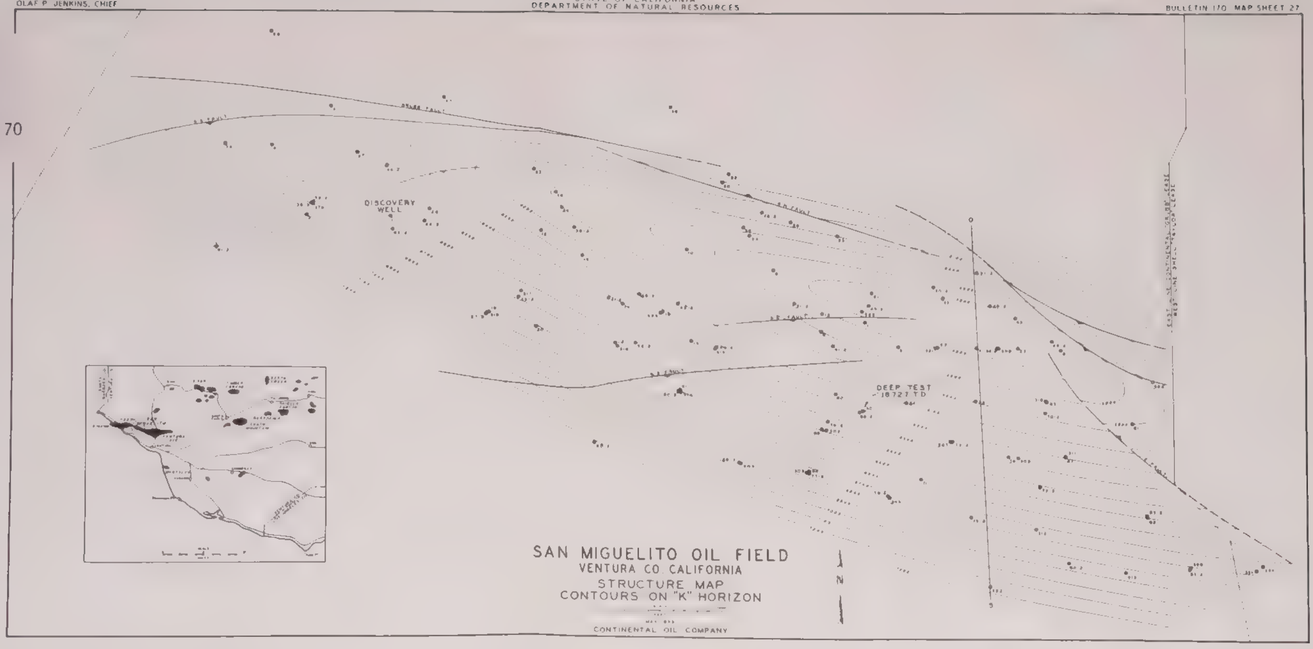
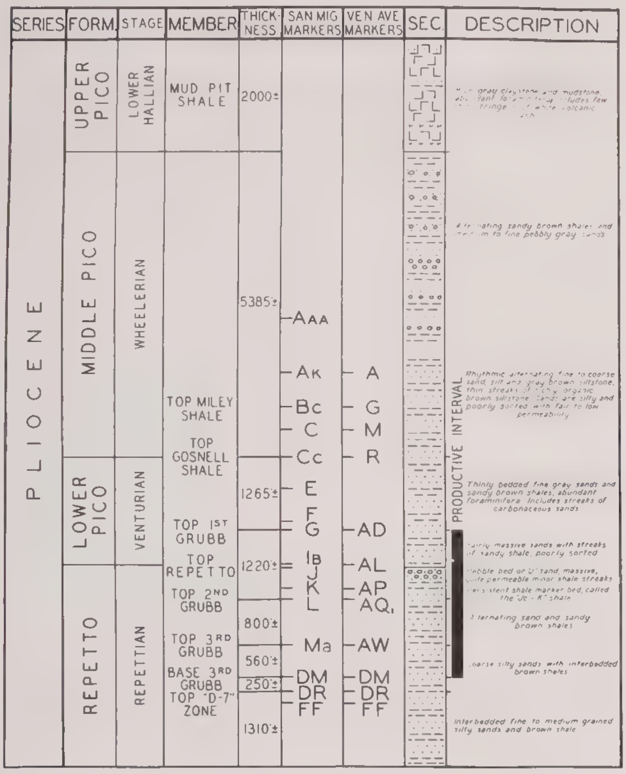
BULLETIN 170 MAP SHEET 27



SAN MIGUELITO OIL FIELD
VENTURA CO. CALIFORNIA
STRUCTURE MAP
CONTOURS ON "K" HORIZON

CONTINENTAL OIL COMPANY

GENERALIZED COLUMNAR SECTION OF THE SAN MIGUELITO AREA


SERIES
FORM.
STAGE
MEMBER
THICKNESS
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VEN AVE MARKERS
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PLIOCENE
UPPER PICO
MIDDLE PICO
LOWER PICO
REPETTO
LOWER HALLIAN
WHEELERIAN
VENTURIAN
REPETTIAN
MUD PIT SHALE
TOP MILEY SHALE
TOP GOSNELL SHALE
TOP 1ST GRUBB
TOP REPETTO
TOP 2ND GRUBB
TOP 3RD GRUBB
BASE 3RD GRUBB
TOP "D-7" ZONE
2000±
5385±
1265±
1220±
800±
560±
250±
1310±
AAA
AK
Bc
C
Cc
E
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G
IB
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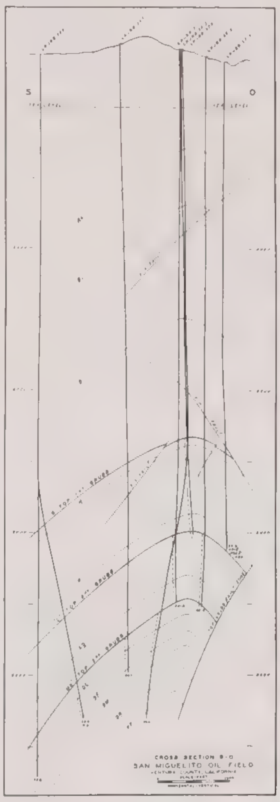
PRODUCTIVE INTERVAL
Alternating sandy brown shales and medium to fine pebbly gray sands
Rhythmic alternating fine to coarse sand, silt and gray brown siltstone, thin streaks of richly organic brown siltstone. Sands are silty and poorly sorted with fair to low permeability
Thinly bedded fine grey sands and sandy brown shales, abundant foraminifera. Includes streaks of carbonaceous sands
Fairly massive sands with streaks of sandy shale, poorly sorted
Pebble bed or "J" sand, massive, quite permeable minor shale streaks
Persistent shale marker bed, called the "Jc - K" shale
Alternating sand and sandy brown shales
Coarse silty sands with interbedded brown shales
Interbedded fine to medium grained silty sands and brown shale



CROSS SECTION S-O
SAN MIGUELITO OIL FIELD
VENTURA COUNTY, CALIFORNIA

A. Amphitheatre Canyon, toward east along south limb of anticline. Outcropping sands and shales are middle Pico. Drilling mast at far end of canyon is over Grubb 80-2.

B. San Miguelito anticline, as exposed in Amphitheatre Canyon.

C. South limb of San Miguelito anticline, toward southwest. The Pacific Ocean and Santa Cruz Island can be seen along left skyline. Located on large mat across canyon are wells Grubb 317 and 33-2.

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 27

GEOLOGY OF THE SAN MIGUELITO OIL FIELD, VENTURA COUNTY

By Richard B. Haines * and Francis E. Minshall †

Introduction. The San Miguelito oil field is on the Ventura anticline 4 miles northwest of Ventura and about midway between the Rincon and Ventura Avenue oil fields. The field was discovered by means of surface geology. The discovery well, Continental Oil Company's No. Grubb 1, was spudded on February 14, 1931, and was completed on November 22 of the same year at a total depth of 6,750 feet, flowing 600 barrels per day of 23° gravity oil, cutting 2.9 percent from 570 feet of penetration in the First Grubb zone. After 7 months, the well was deepened to 7,197 feet, still 250 feet above the bottom of the First Grubb zone, where it was recompleted for 2,375 barrels per day of 30° gravity oil, cutting 3 percent.

For much of the material presented in this paper, the writers have drawn freely from the published work of McClellan and Haines (1951).

Stratigraphy. The section penetrated in exploration and development of the San Miguelito oil field includes beds of uppermost Miocene age and the Repetto and Pico formations of Pliocene age (see columnar section).

Continental Oil Company's well No. Grubb 301 and Chanslor Canfield Midway Oil Company's well Hobson C-11 (Rincon field deep test) both penetrated uppermost Miocene beds. Considerable amounts of oil-saturated sand were encountered. These sands and sandstones are mostly hard, and commonly are calcareous, poorly sorted, and very tight. Interbedded with them are dark brown shales that commonly are slickensided and fractured. In the Grubb 301 well, the top of the Miocene (Delmontian) section is placed tentatively at 12,400 feet, and the top of the Mohnian-stage beds is definite at 16,610 feet.

The Repetto formation falls wholly within the Repettian stage of Natland (1952). It is 3,500 feet thick, and consists of fine to coarse pebbly sands and subordinate interbedded sandy brown shale. The Third and Second Grubb oil zones lie wholly within the Repetto section. The base of the Third Grubb oil zone has been chosen at the "DM" electric-log marker of the Ventura Avenue field, and is 250 feet stratigraphically above the "DR", or top of the D-7 zone (see columnar section). The top of the Third Grubb oil zone and base of the Second Grubb oil zone is the "Ma" marker. "L" is the top of the second Grubb oil zone, and "Ib" is approximately the top of the Repetto formation. The "K" marker occurs at the base of the thickest and most persistent shale member, and is used as the key contour horizon for the field (see structure map).

The lower part of the lower Pico formation contains the upper half of the First Grubb oil zone, the top of which is located at the "G" marker. The total thickness of lower Pico beds is 1,900 feet; these fall within the Venturian stage.

The middle Pico formation, about 5,385 feet thick, is Wheelerian, with the Gosnell shale at the base. These strata are rhythmically alternating sand, silt, shale, and coarse pebbly sands.

The upper Pico formation is locally termed the Mud Pit shale, and consists of 2,000 feet of massive and well-bedded dark gray, brown, and blue clay, silt, and mudstone. Some geologists regard the upper part of the Mud Pit shale as Pleistocene, and correlate it with the formation containing the Timm's Point fauna at San Pedro. Natland (1952) assigns the Mud Pit shale to his lower Hallian stage.

Structure. The major structural features of the San Miguelito field are the closed anticline and the Grubb thrust fault (see map). The Grubb fault is the upper and southerly branch of the Padre fault zone as it occurs in the westerly part of the field. The San Miguelito structure is an asymmetrical closed anticline that is cut by the south-dipping Grubb fault at depth (see cross section). It lies on the westward continuation of the Ventura Avenue anticlinal fold, and trends N. 74° W. The productive area is approximately 1¾ miles long and ½ mile in maximum width. Dips are steeper on the north flank of the fold, and are vertical at the top of the Grubb fault zone in the western part of the field. The average dip within the productive limits on the south flank of the fold is 40°.

The Grubb fault trends slightly oblique with respect to the axis of the fold, and crosses the axis at the west end of the field. The average dip of the fault near the center of the field is 55° toward the south. The deep test well, Grubb 301, penetrated 4,300 feet of disturbed beds, whereas in Grubb 38, located about 3,000 feet to the northwest, there is only about 2,200 feet of disturbed material. The Grubb fault in the San Miguelito field seems to have originated in the steep limb of an overturned or nearly overturned fold, and the probable plane of major movement is bounded both above and below by a thick zone of attenuated, fractured, and crushed beds. The actual slippage on the fault plane varies greatly, according to the amount of attenuation of the beds before actual breaking occurred. The south block has moved upward with respect to the north block, resulting in a dip-slip movement on the combined Padre and Grubb faults of as much as 4,000 feet.

General summary of well data San Miguelito field.

	First Grubb zone	*Second Grubb zone*	*Third Grubb zone*	*Total*
Discovery				
Date	11-22-31	Apr. '44	Aug. '49	
Discovery Well No.	1	31-2	301	
Initial production, barrels per day	616	1,558	1,311	
Production of discovery well to February 1, 1953, barrels	1,792,785	430,012	350,415	
Production data to February 1, 1953				
Cumulative production, barrels	19,330,250	10,198,438	2,926,627	32,455,315
Average production, barrels per day	3,016	3,862	2,901	9,779
Number wells producing	52	36	23	111
General data				
Elevation range in existing wells				
High	1,132	1,105	1,067	
Low	271	337	352	
Stratigraphic thickness, average feet	1,180	1,045	604	2,813
Net sand thickness, average feet	683	564	277	1,524
Total depth of wells, average feet	7,070	8,294	8,950	
Average permeability (md)	90	30	33	
Average porosity (%)	20.6	19	14.2	

Minor faults near the axis of the anticline evidently represent adjustments during the process of folding. Most of them are parallel with the fold axis, and range from a few feet to nearly 300 feet in apparent vertical displacement. All are of reverse or thrust type, and they die out along both strike and dip. Several small faults near the east end of the field strike diagonally across the anticline, and range from 20 feet to 250 feet in displacement. Movement along these was of reverse type and must have been essentially dip-slip, because the axis of the fold does not seem to have been displaced appreciably in a horizontal direction.

Relation of Structure to Oil Accumulation. Accumulation of oil in the San Miguelito field has been primarily that of ordinary anticlinal entrapment. The effect of the Grubb fault has been to reduce the permeability of the sands on the north flank of the anticline and in the fractured fault zone, but these sands are oil-saturated where they lie on structure. In the south flank of the structure, oil accumulation in all three Grubb zones is bounded by edge water. Glenn (1950) states that water encroachment on the south flank has been ineffective in maintaining reservoir pressure, or in affecting the behavior of the solution gas drive. There is no water drive on the north flank.

The productive limits of the field are determined on the west, north, and at depth by the compression and compaction associated with the Grubb fault. Water level determines the limits on the south flank, and a partial barrier to production at the east end probably is caused by faulting.

Current Drilling Activity. Near the eastern Grubb lease line, well No. Grubb 324 is nearing completion. The productive zone appears to be in an extension of the Ventura Avenue field "D-block"; it is entirely separate from the normal Grubb oil zones. The extent and productivity of this extension are yet to be determined.

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McClellan, H. W., and Haines, R. B., 1951, San Miguelito oil field, Ventura County, California: Am. Assoc. Petroleum Geologists Bull., vol. 35, pp. 2542-2560.

Natland, M. L., 1952, Pleistocene and Pliocene stratigraphy of southern California: Paper read before the Am. Assoc. Petroleum Geologists, Los Angeles, California, March 24-27, 1952. See also chart in Pacific Petroleum Geologist, vol. 7, no. 2, p. 2, 1953.

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DIVISION OF MINES
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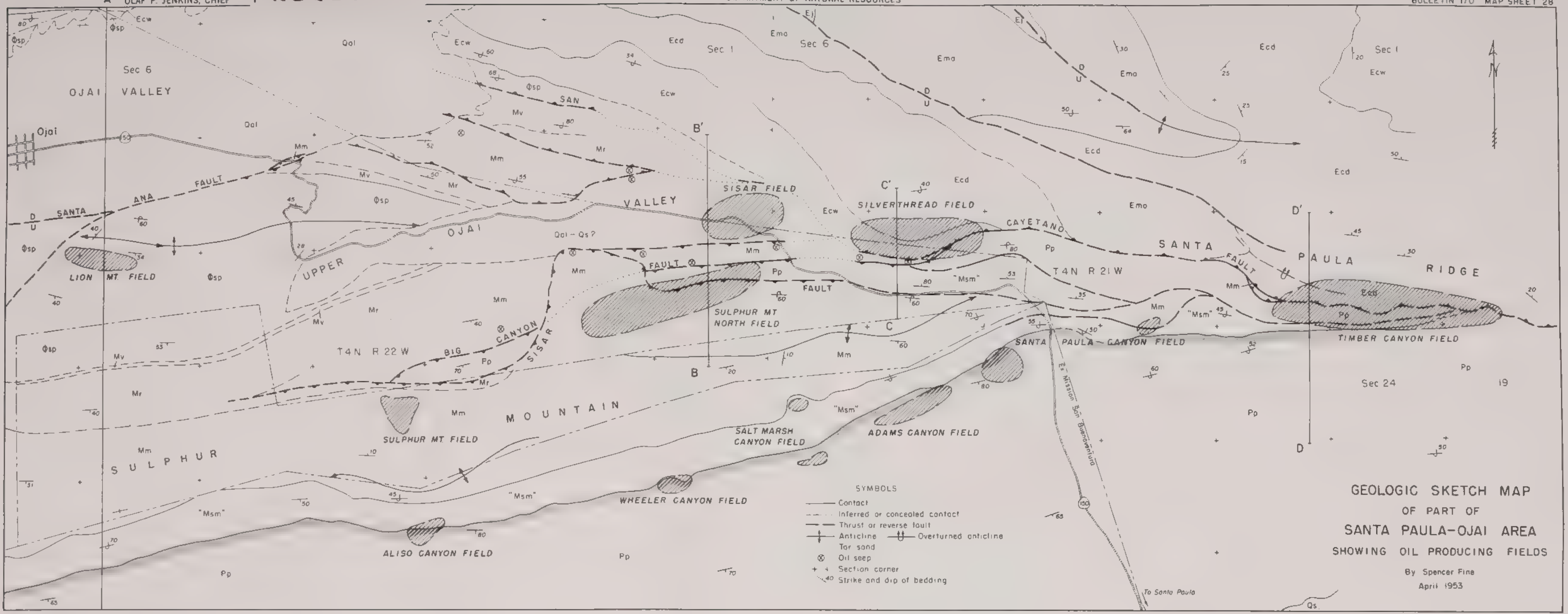
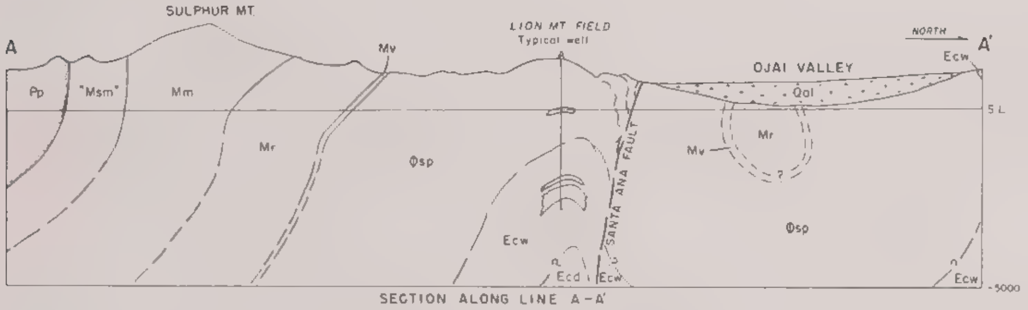


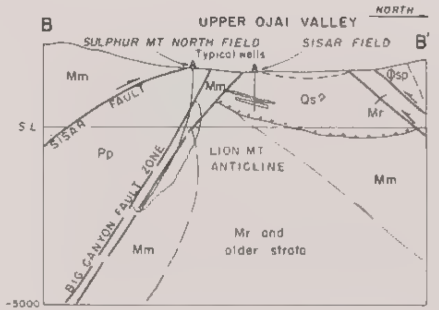
GEOLOGIC SKETCH MAP
OF PART OF
SANTA PAULA-OJAI AREA
SHOWING OIL PRODUCING FIELDS

By Spencer Fine
April 1953

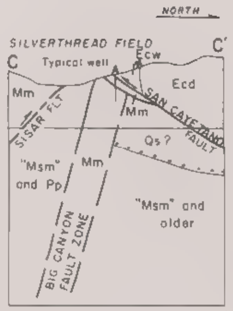


SECTION ALONG LINE A-A'

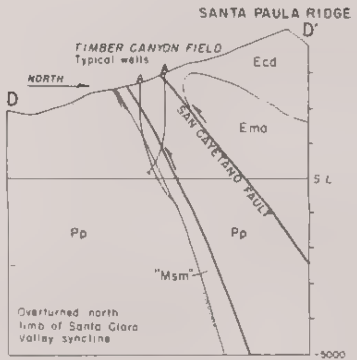
SYMBOL	FORMATION	THICKNESS
Qal	Alluvium	700
Qs	Saugus	6000
Pp	Pico	12,000
"Msm"	"Santa Margarita"	1800
Mm	Monterey	2000
Mr	Rincon	1500
Mv	Vaqueros	0-400
Φsp	Sespe	4500
Ecw	Coldwater	2500
Ecd	Cozy Dell	3000
Emo	Matilija	3300
Ej	Juncal	5000
	Total	42,700±



SECTION ALONG LINE B-B'



SECTION ALONG LINE C-C'



SECTION ALONG LINE D-D'

NAME OF OIL FIELDS	YR OF DISC	TOTAL WELLS DRLD	WELLS PROD JAN '53	AVER GRAV	TOTAL BBLS PROD TO JAN '53	PRODUCING ZONE				
						AGE	STAGE	FM NAME	TYPE OF RESERVOIR	TYPE OF TRAP
SISAR	1885	39	26	14°	INCL WITH SILVERTHREAD	PLEIST.	HALLIAN?	SAUGUS ?	SAND	LENSING SANDS AFFECTED BY FAULT
ALISO CANYON	1875	10	0	26°	2,138,000	PLIOCENE	REPETTIAN	PICO		TAR SEAL AFFECTED BY FAULTS
WHEELER CANYON		29	5							
SALTMARSH CAN.(LOWER)		21	0							
ADAMS CANYON		40	4							
SANTA PAULA CANYON		60	15							
TIMBER CANYON	1885	55	24	34°	1,195,215					
SILVERTHREAD	1885	70	31	22°	3,082,233	MIOCENE	MOHNIAN TO RELIZIAN	MONTEREY	FRAC SH. AND SD.	
SULPHUR MT NORTH	1912	25	20	21°	665,950		MOHNIAN			FAULT
SULPHUR MT	1927	14	1	16°	99,997		LUISIAN TO RELIZIAN		FRAC. SH	
LION MT	1935	14	0	18°	77,800	OLIG	REFUGIAN?	SESPE	SAND	ANTICLINAL
	1948	6	4	28°	52,628	EOCENE	A-1	COLDWATER		

STATISTICAL DATA FROM CALIF DIV OIL & GAS & CONSERVATION COMMITTEE REPORTS

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 28

GEOLOGY AND OCCURRENCES OF OIL IN THE OJAI-SANTA PAULA AREA, VENTURA COUNTY

By Spencer F. Fine [*]

The Santa Paula-Ojai fields are of minor importance in terms of oil production from the general Ventura basin area, but they are of interest because represented among them are varied causes for oil accumulation, kinds of reservoirs, and ages of producing zones. Approximately 40,000 feet of post-Cretaceous sediments, half of them Pliocene in age, are involved in the complex structure of the area.

The dominant structural feature in the area is the San Cayetano fault, a north-dipping thrust that is approximately 20 miles in length. About 4 miles east of the map area, where Eocene rocks have been thrust over Quaternary strata, there is approximately 30,000 feet of apparent stratigraphic throw. The structure of Ojai Valley is synclinal (section A-A′), and the formations that border it on the north and south are overturned. Lion Mountain is an anticline in Oligocene beds that plunges eastward beneath the upper Ojai Valley (see map). The east part of upper Ojai Valley is a graben that has been downdropped between the San Cayetano and Big Canyon faults (sections B-B′, C-C′), and has been partly filled with nonmarine clastic strata of Quaternary (?) age. South of Lion Mountain and across the westerly end of Sulphur Mountain is a south-dipping homocline that involves strata of Oligocene to Pliocene age, but near the easterly end of Sulphur Mountain the structure of the Miocene Monterey formation above the Sisar fault is an anticlinal fold in which both limbs are overturned (see map). The block between the Sisar and Big Canyon faults is essentially synclinal, and is composed of rocks younger in age than those on either side. The Lion Mountain and Sulphur Mountain folds plunge and converge eastward, and have been overridden by Eocene formations above the San Cayetano fault in the Timber Canyon area.

Oil seeps and tar sands are common in this general area, especially in the basal Pico tar sands, which crop out almost continuously for approximately 15 miles along the south side of the Sulphur Mountain-Santa Paula Ridge. The Big Canyon fault zone is a source of numerous tar seepages, some of them now active, along its surface trace (see map). In 1947 new commercial production was found in the Sulphur Mountain North field. The strata of the producing zone dip 50° south at the west end of the field, but along the strike to the east they become overturned and are truncated up dip by the top of the Big Canyon fault zone (also called the North Sulphur Mountain fault). Development wells usually are directed southward in order to gain the maximum amount of stratigraphic penetration while maintaining a relatively high structural position beneath the fault. As much as 2,000 feet of hole may be left open for production. The Timber Canyon field has had renewed development since 1948. Here, because of conditions not completely understood, wells drilled into the basal Pico sands downdip from the exposed tar sands produce from 10 to 600 b/d of relatively clean, high-gravity oil. There appears to be no structural interruption of the sands between the outcrop and the positions as encountered in the wells, although small cross faults do exist. The oil sand is overturned, dipping northward about 70°, and the height of the oil column is at least 3,000 feet. A few wells have been drilled directly down the dip of one of the sands with success (section D-D′).

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[*] District Geologist, Richfield Oil Corporation, Ojai.

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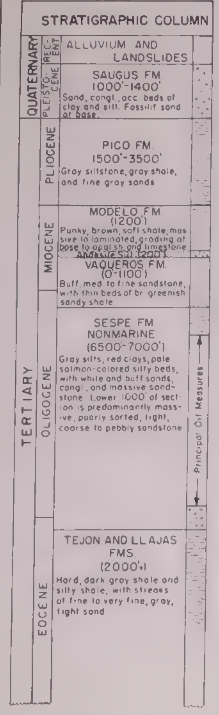
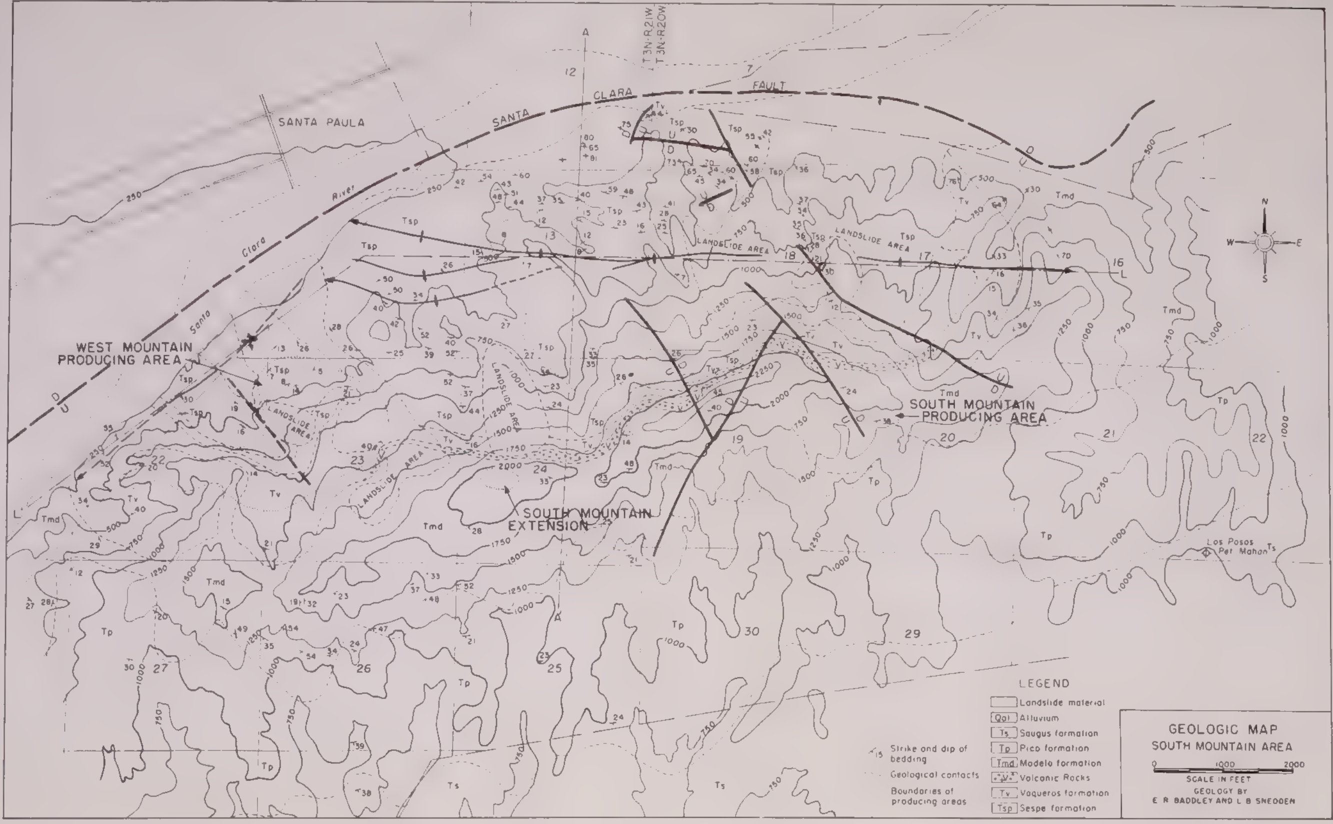
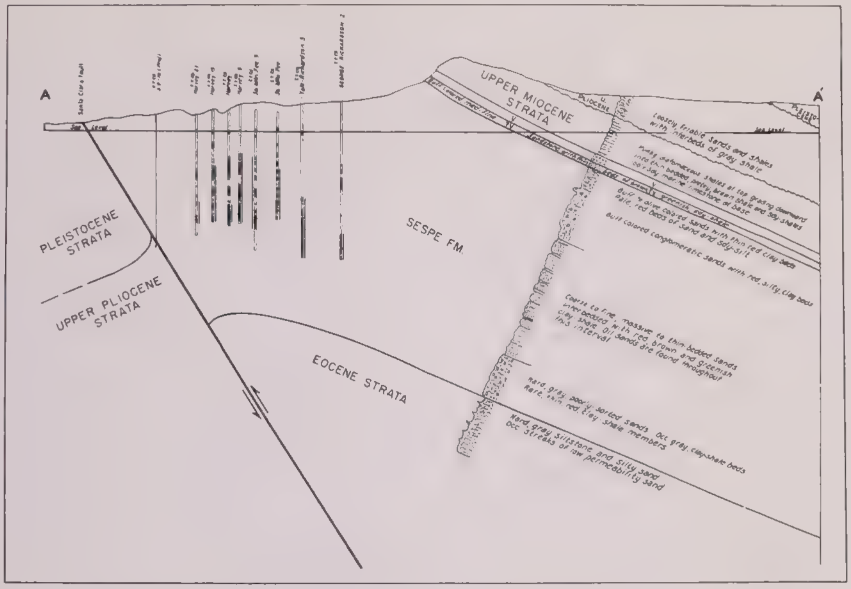
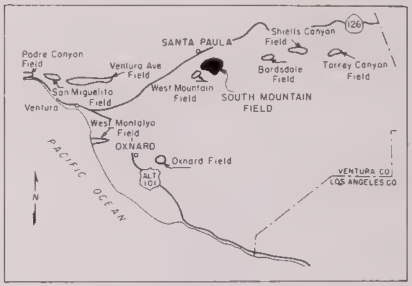

STRATIGRAPHIC COLUMN
QUATERNARY
RECENT
ALLUVIUM AND LANDSLIDES
PLEISTOCENE
SAUGUS FM. 1000'-1400'
Sand, congl., occ. beds of clay and silt. Fossilif sand at base.
TERTIARY
PLIOCENE
PICO FM. 1500'-3500'
Gray siltstone, gray shale, and fine gray sands
MIOCENE
MODELO FM. (1200')
Punky, brown, soft shale; massive to laminated, grading at base to opal sh. and limestone
Andesite Sill (200')
VAQUEROS FM. (0'-1100')
Buff, med. to fine sandstone, with thin beds of br. greenish sandy shale
OLIGOCENE
SESPE FM NONMARINE (6500'-7000')
Gray silts, red clays, pale salmon-colored silty beds, with white and buff sands, congl., and massive sandstone. Lower 1000' of section is predominantly massive, poorly sorted, tight, coarse to pebbly sandstone
Principal Oil Measures
EOCENE
TEJON AND LLAJAS FMS. (2000'±)
Hard, dark gray shale and silty shale, with streaks of fine to very fine, gray, tight sand




A
A'
Santa Clara fault
Sea level
PLEISTOCENE STRATA
UPPER PLIOCENE STRATA
SESPE FM.
EOCENE STRATA
UPPER MIOCENE STRATA
U. MIOCENE
PLEISTOCENE
Loosely friable sands and shales with interbeds of gray shale
Punky diatomaceous shales at top grading downward into thin bedded, pretty brown shale and sdy shales
Buff to olive colored sands with thin red clay beds
Pale, red beds of sand and sdy-silt
Buff colored conglomeratic sands with red, silty, clay beds
Coarse to fine, massive to thin-bedded sands interbedded with red brown and greenish clay shale. Oil sands are found throughout this interval
Hard, gray, poorly sorted sands. Occ gray, clay-shale beds
Rare, thin red clay shale members
Hard, gray siltstone and silty sand
Occ streaks of low permeability sand



INDEX MAP

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 29

GEOLOGY OF THE SOUTH MOUNTAIN OIL FIELD, VENTURA COUNTY

By E. R. Baddley *

The westerly advance of oil field discoveries along the Oak Ridge anticline, beginning at Torrey Canyon in 1891, reached the western end of this structural uplift at South Mountain in 1915. The discovery well, Texas Company South Mountain No. 1, was completed in April 1915 for 25 B D of 25° gravity clean oil, from the perforated interval 1492-2960 feet.

Approximately 90 wells, all drilled by cable tools, were completed between 1915 and 1928. Rotary drilling was begun in 1928, but very few new development wells were drilled until 1942, which marked the beginning of an era of exploration guided by new tools and new methods of interpretation, chief among which was the electric log. Almost as much oil (15,660,000 bbls.) has been produced from the field since 1942 as was obtained during the preceding 27 years.

The recent increased production from the 38-year old field has been due largely to improved engineering practices and electric-log interpretation. The problems of extremely rugged topography and large landslides in the area have been overcome by directional drilling from specially designed islands.

The structure that houses the multiple reservoir sands of the nonmarine Sespe formation (Oligocene) is one of the classic anticlines in the state. Its qualifications as a prospective oil structure are abundantly exposed in numerous rugged canyons and cliffs, yet 24 years elapsed between the discovery of oil on the same uplift at Torrey Canyon and the first test at South Mountain. The core of the fold is composed of nonmarine strata, including gray sandstones and variegated finer grained rocks, that are similar to those in all of the folds along this trend.

The South Mountain anticline, including its subsidiary West Mountain fold, is steeper on its north flank than on its south flank. As revealed on the surface, this asymmetry is accentuated by the close proximity of the north flank to the Santa Clara (Oak Ridge) thrust fault, and has not yet been satisfactorily correlated with conditions in the subsurface. The development and exploratory holes have been concentrated on the south flank of the fold, although subsurface contours on top of the oil sands and electric-log points do not indicate an asymmetry at depth to match that shown on the surface.

The Santa Clara (Oak Ridge) fault has thrust beds of the Sespe formation over Pliocene and Pleistocene beds to the north, involving a displacement of several thousands of feet. This major break is important in its relation to the oil field primarily in terms of the origin of the oil that has accumulated in the nonmarine sands. The source of this oil is still very much a matter of speculation, and the only point of common agreement seems to be that the source was in marine beds. The popular conversational theories relative to the route of migration of oil in this field include:

(1) The Santa Clara thrust fault may have afforded entrée to the nonmarine beds for the oil generated in the marine section beneath the fault. The recent discovery of oil between the Shiells Canyon and Bardsdale fields in beds of late Pliocene age that lie beneath the fault and beneath oil-bearing Sespe strata may lend support to this idea. However, not far west of the same area a minor amount of oil has been produced from beds below the fault, whereas nonmarine Sespe beds in the immediately overlying anticline were found to be barren of oil showings. Sufficient data still are lacking to show that the fault plane has been a barrier to, or a conduit for, fluid migration.

(2) An upward migration from Eocene marine beds that underlie the Sespe formation is slightly more plausible, although a thousand feet of barren, hard, very tight, gray sandstone separates the marine Eocene beds below from the oil measures of the nonmarine section above. The apparent low organic content of the Eocene hard siltstones and shales, together with the low oil productivity of this section, does not seem to rate it as a prolific source of oil.

(3) The closest marine beds of an age equivalent to the nonmarine oil-sand section of the Sespe formation are 65 to 70 miles northwest of South Mountain, along the coast near Gaviota in Santa Barbara County. No such beds are present to the east. The boundaries of the basin of Sespe deposition, as now known, leave little room for the occurrence of correlative marine beds nearer than those of the Gaviota area. The idea of lateral migration of oil from this distant area to the South Mountain field does not seem to have attracted much vigorous support[1]

Four wells at South Mountain and one on West Mountain have penetrated and explored the Eocene section. No commercial accumulation similar to that from Eocene beds in the Barsdale field, 5 miles to the east, has yet been found. It remains to be determined whether this lack of oil should be attributed to unfavorable sand permeabilities or to unfavorable structural relations.

The South Mountain field is a low-pressure gas-drive field. The water problem is simple, as is indicated by the fact that less than 280 barrels of water per day is obtained from 125 producing wells on The Texas Company leases.

Prior to electric logging, the erratic occurrence of so-called bottom water gave rise to the belief that no uniform water table was present. Instead, a series of very low-head waters was assumed to be confined to local sand lenses. More recent studies, based on electric-log interpretation, indicate the existence of a water table which, due to faulting and tilting, has extended the producing area considerably farther down the south flank than on the north flank of the anticline.

SOUTH MOUNTAIN FIELD

Discovery well: South Mountain No. 1
Date of discovery: 1915
Initial production: 25 barrels per day (Initial production for subsequent well varies from 25 to 600 barrels per day)
Gravity: 25 degrees
Type of oil: Mixed paraffine and asphalt base. Waxing of tubing and rods is a major problem
Total producing wells: 225
Depth range: 3000 to 6500 feet
Average net oil sand in perforated interval: 1000 feet
Average sand permeability: 72 Mdcys.
Cumulative production to 1953, barrels: 39,642,000
Estimated ultimate production per acre, in barrels: 40,000
Productive acres: 1500

NOTE: The wells are long lived. The discovery well (38 years old) is still pumping 4 barrels per day of clean oil. Very few of the original completed wells have been abandoned.

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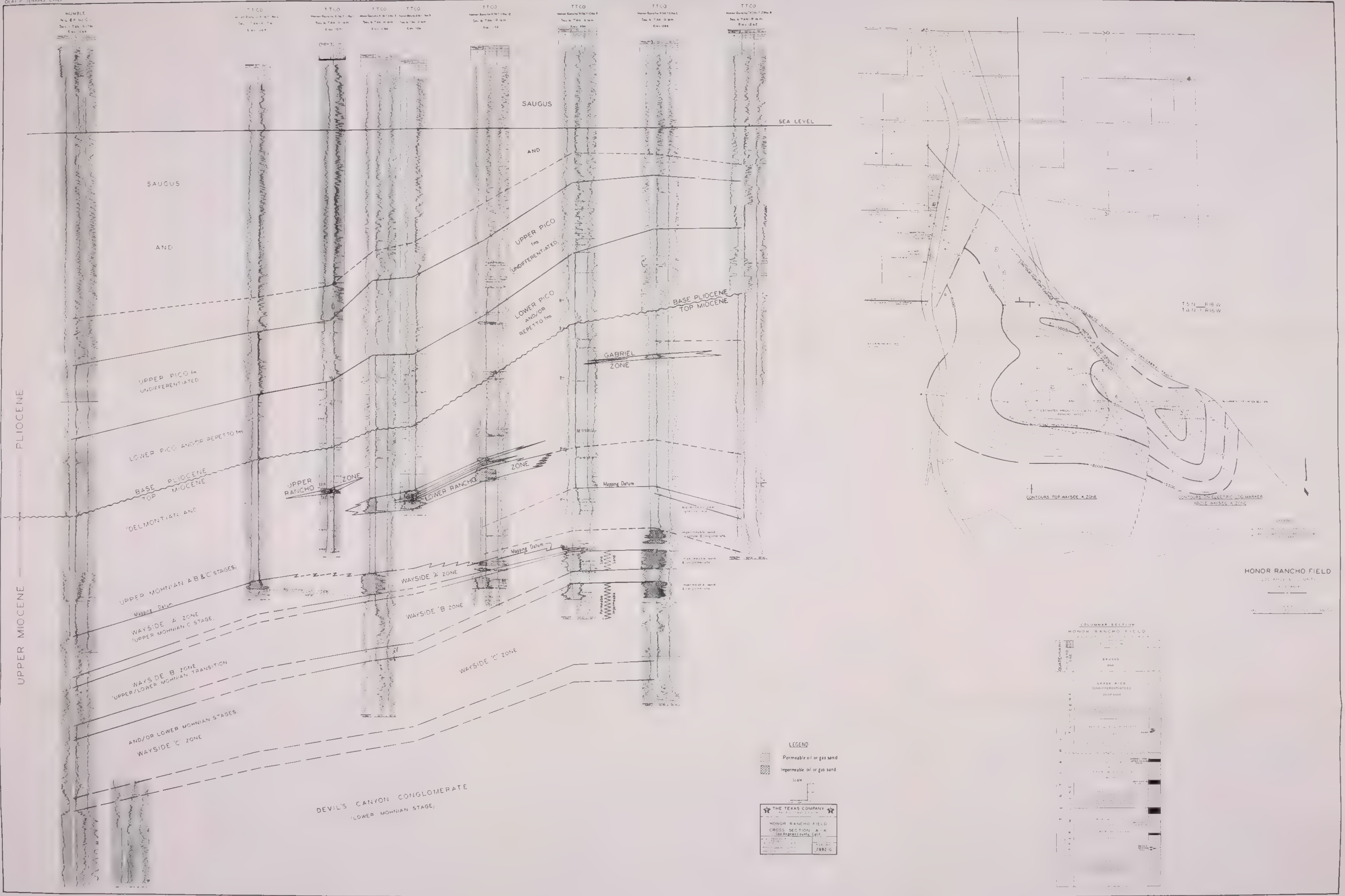
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 170, MAP SHEET 30


HUMBLE
T.T.CO.
SAUGUS
AND
SEA LEVEL
UPPER PICO fm (UNDIFFERENTIATED)
LOWER PICO AND/OR REPETTO fm
BASE PLIOCENE
TOP MIOCENE
GABRIEL ZONE
UPPER RANCHO ZONE
LOWER RANCHO ZONE
Mapping Datum
PLIOCENE
UPPER MIOCENE
UPPER PICO fm UNDIFFERENTIATED
LOWER PICO AND/OR REPETTO fm
DELMONTIAN AND
UPPER MOHNIAN A B & C STAGES
WAYSIDE A ZONE (UPPER MOHNIAN C STAGE)
WAYSIDE B ZONE (UPPER/LOWER MOHNIAN TRANSITION
AND/OR LOWER MOHNIAN STAGES
WAYSIDE 'C' ZONE
WAYSIDE 'A' ZONE
WAYSIDE 'B' ZONE
DEVIL'S CANYON CONGLOMERATE (LOWER MOHNIAN STAGE)
LEGEND
Permeable oil or gas sand
Impermeable oil or gas sand
Scale
THE TEXAS COMPANY
HONOR RANCHO FIELD
CROSS SECTION A-A'
Los Angeles County, Calif.
2892-G
T5N R16W
T4N R16W
APPROXIMATE SURFACE TRACE OF SAN GABRIEL FAULT
-5000
-5500
-6000
CONTOURS TOP WAYSIDE A ZONE
CONTOURS ON ELECTRIC LOG MARKER ABOVE WAYSIDE A ZONE
HONOR RANCHO FIELD
COLUMNAR SECTION
HONOR RANCHO FIELD
SAUGUS
AND
UPPER PICO

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GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 30

GEOLOGY OF THE HONOR RANCHO OIL FIELD, LOS ANGELES COUNTY

By Donald G. Herring, Jr.*

The Honor Rancho oil field is located on the Los Angeles County Wayside Honor Farm in section 6, T. 4 N., R. 16 W.; section 31, T. 5 N., 16 W., and section 36, T. 5 N., R. 17 W. It was discovered August 22, 1950, with the completion of The Texas Company well Honor Rancho "A" (NCT-1) No. 1, flowing 1,414 B/D. of 35.3° gravity oil from the interval 5,300-5,340 feet. As of October 1, 1953, twenty-two oil wells and four dry holes had been completed in the field, and daily average production was approximately 3,500 barrels. The cumulative production has amounted to approximately 2,500,000 barrels.

There are two main producing zones in the field, both in the upper Miocene section (Delmontian and Mohnian faunal stages). The lower zone, the Wayside, consists of sands, shales, and conglomerates ranging in age from Mohnian "C" to lower Mohnian, with a maximum overall thickness of approximately 2,000 feet. The Wayside sands are present beneath most of the field, but become impermeable to the northeast and probably also to the northwest by grading into siltstone or tight conglomerate. Oil accumulation is believed to have been controlled primarily by these changes in permeability

The Wayside has been locally divided into three sub-zones, designated "A," "B," and "C," that constitute separate productive or potentially productive reservoirs. All but one of the 16 wells currently producing from the Wayside have been completed in the "A" zone, which appears to be a single, continuous reservoir with an oil-water contact ranging from approximately –5,400 feet at the north end of the field to –5,490 feet at the south end. This zone produces approximately 90 percent of the oil in the field. The Texas Company well Honor Rancho "A" (NCT-2) No. 5 is completed in the "C" zone, the "A" zone here being thin and containing gas. The "B" zone has not been found commercially productive to date. Average gravity of the Wayside oil is 36°.

The second main producing zone, the Rancho, overlies the Wayside by approximately 700 to 1,500 feet. It consists of lenticular sands and conglomerates erratically distributed within a shale and siltstone section, of Delmontian and Mohnian "A" age, that ranges in overall thickness from 1,500 to 2,500 feet. The productive Rancho sands have a maximum known thickness of 244 feet in the Texas Company well Honor Rancho "A" (NCT-1) No. 16, and shale out completely in a relatively short distance to the west, north, and east. At least three separate sands are thought to be productive in this zone. The producing sands in the discovery well, The Texas Company Honor Rancho "A" (NCT-1) No. 1, and in the Honor Rancho "A" (NCT-2) No. 2 and No. 7 (known locally in these latter two wells as the Gabriel zone) are believed to be several hundred feet stratigraphically higher than the sand producing in Honor Rancho "A" (NCT-1) No. 3, No. 6, and No. 16. Six wells were producing from the Rancho zone (including the Gabriel sands) as of October 1, 1953. Gravity of the oil averages 35.9°.

The correlation of the producing zones of the Honor Rancho field with those of the adjacent Castaic Hills field to the northwest is not clear. Meager paleontological data suggest that the Wayside zone of Honor Rancho may be somewhat younger than the Sterling zone of Castaic Hills, whereas electric-log correlations indicate that the reverse may be true, or that the two zones may be approximately equivalent. Additional subsurface data are necessary to solve this problem.

Structurally the Honor Rancho field, as contoured on or near the top of the Wayside zone, is a closed anticline that plunges to the west and northwest. There is some evidence in the surface beds for faulting along the northeast edge of the field, and this faulting is believed by some geologists to be a northwesterly extension of the San Gabriel fault zone, and to connect with the Palomas fault to the northwest. No direct evidence of this fault has been found in wells drilled to date, however, and closure in the producing sands is not believed to be dependent on faulting; it is primarily stratigraphic, as pointed out above and as illustrated by the accompanying cross-section. Indeed, the field is rather unusual because of the small amount of faulting involved. With the exception of a probable high-angle thrust fault that is cut by The Texas Company well Honor Rancho "A" (NCT-1) No. 13 and is believed to separate the Honor Rancho field from the Castaic Hills field, no good evidence of faulting has been encountered in any of the wells.

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* Geologist, The Texas Company, Los Angeles

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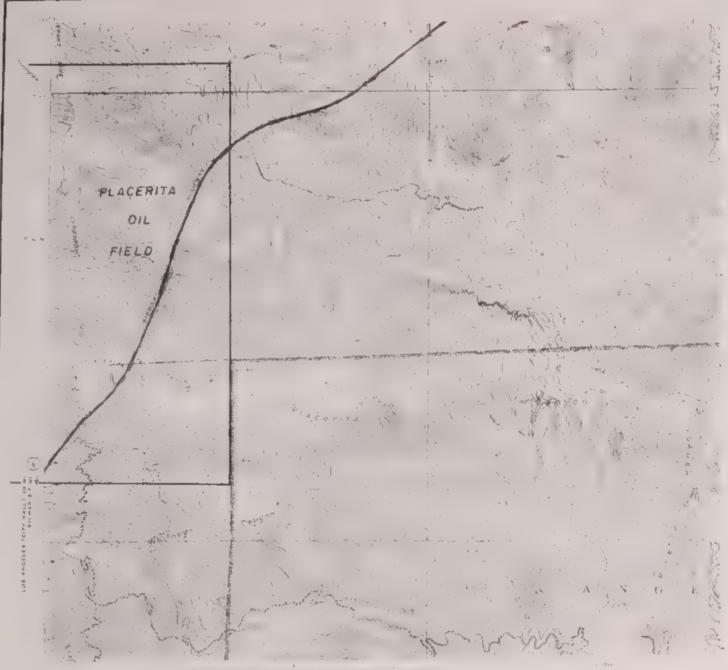
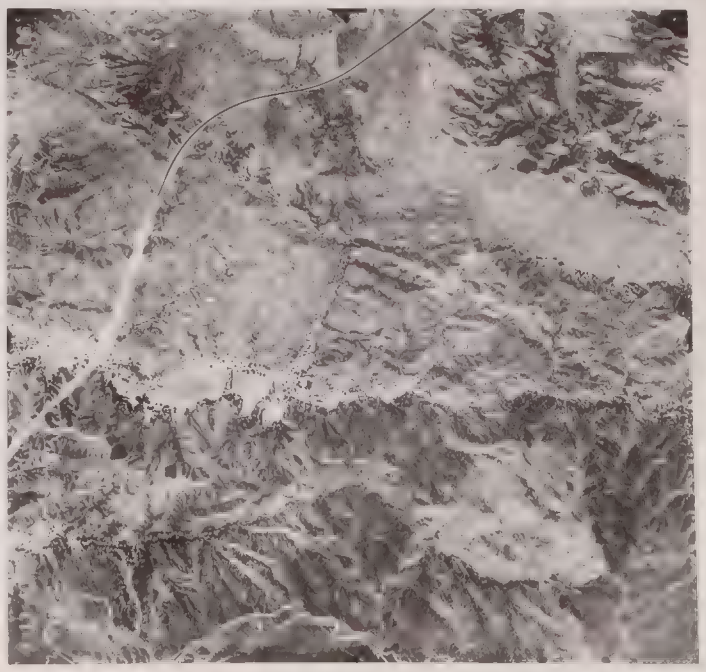


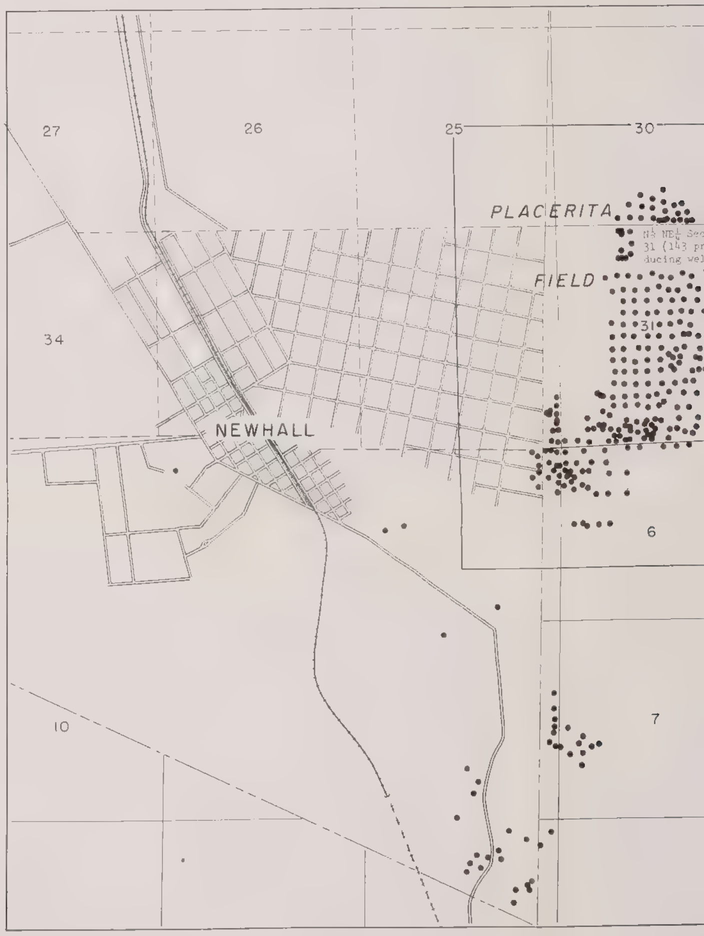
TOPOGRAPHIC MAP



AERIAL PHOTOGRAPH

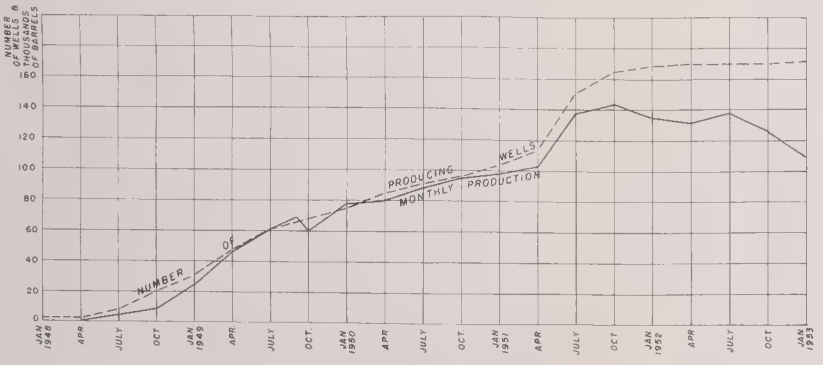
SUMMARY OF ROCK FORMATIONS

Age		Formation or member	Description	Maximum thickness	Economic interest
Recent		Alluvium	Stream sands and gravels of Placerita Canyon and Santa Clara River	100	Water supply. Gold in Placerita Canyon.
		Unconformity			
Upper Pleistocene		Younger terrace deposits	Elevated, but unfolded, older alluvium.	175	Gold in Placerita Canyon.
		Older terrace deposits	Similar to younger terrace deposits, but affected by folding and faulting.	500	None recognized.
		Major Unconformity			
Lower Pleistocene		Saugus formation	Continental sandstone and conglomerate	2000	Barren in the oil field.
		Unconformity, but no angular discordance in oil field			
Upper Pliocene	Pico formation	Sunshine Ranch member	Continental and brackish-water conglomerate, greenish sandstone and mudstone, thin beds of fresh-water limestone, redbeds.	1300	Some oil-saturated sands (probably includes "Upper Kraft shale series" of Willis (52)).
		Upper Pico member	Coarse to fine marine sandstone and conglomerate; fossiliferous uppermost Pliocene (probably Santa Barbara zone).	1000	Oil sands (includes upper part of "Upper Kraft zone" of Willis (52)).
Middle Pliocene		Lower Pico member	Marine sandstone and conglomerate; massive fine sandstone and siltstone; fossiliferous calcareous sandstone beds (San Diego fauna).	700	Oil sand and seeps (probably includes lower part of "Upper Kraft zone" of Willis (52)).
		Unconformity			
Lower Pliocene	Repetto fm.	Repetto siltstone member	Marine brown and gray siltstone and fine sandstone; conglomerate	300	Some oil sand and seeps in exposures.
		Elsmere member	Marine fossiliferous coarse sandstone and conglomerate, continental at north end	300	Oil sand and seeps N. of area mapped (Probably essentially equivalent to "Lower Kraft zone" of Willis (52)).
		Unconformable on basement			
Upper Miocene		Modelo formation	Not exposed in oilfield; in subsurface of western part of field. Marine brown sandstone, shale; interfingering continental beds.	1500	Not productive in Placerita field; has produced in Tunnel area (Willis 52).
		Unconformity in outcrop north of mapped area.			
		Mint Canyon formation	N. of San Gabriel fault only. Continental sandstone and conglomerate; tuff beds; lake beds.	2400	None recognized.
		Not in contact			
Eocene and Paleocene		Domengine and Martinez formations	Well-indurated shale, sandstone, conglomerate. Domengine, Capay, and Meganos recognized in the subsurface.	2000	Reservoir for light oil in nearby fields; non-productive in Placerita field.
		Major unconformity			
Pre-Tertiary		Granitic rocks; Rubio diorite gneiss; Placerita series.	Irregular remnants of Placerita metasedimentary rocks (Paleozoic?); Rubio diorite gneiss (late Paleozoic?); both intruded by granitic rocks (U. Jur.-Cret.?)		Reservoir rock for a little light oil in Placerita schist area.



PRODUCING WELLS IN NORTHWEST PART NEWHALL OIL FIELD
INCLUDING PLACERITA OIL FIELD

Modified July 1953 from map of NEWHALL OIL FIELD No 18A Revised Jan. 195
and No 63 CALIFORNIA DIVISION OF OIL AND GAS



PRODUCTION DATA, KRAFT–YORK AREA, PLACERITA OIL FIELD
1948–49 Barton & Sampson (49), 1950–52 Musser (unpub.)
California Division of Oil and Gas

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA
MAP SHEET NO. 31

GEOLOGY OF THE PLACERITA OIL FIELD, LOS ANGELES COUNTY

By Gordon B. Oakeshott *

Introduction. The Placerita oil field extends over section 31, T. 4 N., R. 15 W., and the borders of adjoining sections on the north, west, and south at the western end of the San Gabriel Mountains about 2 miles east of Newhall. The field is crossed by Sierra Highway (U.S. 6) and by a paved Los Angeles county road in Placerita Canyon. It is 1 mile north of the Whitney Canyon area, abandoned in 1937; 1½ miles north of the Elsmere area; and 2½ miles due west of the Placerita schist area, which produced a little high-gravity oil from basement rocks several years ago. These three areas had no production in 1952. The Placerita field is divided into the Juanita area on the north and the Kraft-York area on the south by the northwest-trending Orwig fault. The Juanita area produced 1,887,000 barrels of 21.0° gravity oil in 1952, while the Kraft-York area produced 1,571,000 barrels of 12.7° gravity oil.

The Kraft-York area was discovered in 1920 by the Equity Oil Company, which completed Daisy 1 (now Guiberson Oil Company York 1) for a few barrels of 14° gravity oil at a depth of 975 feet. Four wells were drilled between 1920 and 1933, and produced from 6 to 19 barrels per day. In April 1948, the Nelson-Phillips Oil Company rediscovered the area when it brought in Kraft 1 in Placerita Canyon flowing 70 to 100 barrels per day of 15.6° oil from a depth of 580 to 717 feet. In January 1949, Ramon Somavia brought in Juanita 1 flowing 340 barrels per day of 22.4° gravity oil, with the bottom of the producing zone at 1,830 feet. This well, about a mile north of Nelson-Phillips' Kraft 1, was the discovery hole in the Juanita high-gravity area. There followed a period of unrestricted production in this area, as the State Spacing Act was declared unconstitutional by the California Superior Court. A town-lot drilling campaign sent production skyrocketing in the Juanita area to more than 860,000 barrels per month in September 1949. Production in the area fell very rapidly to a July 1951 figure of slightly more than 200,000 barrels, and has gradually declined since that time.

Stratigraphy. The Placerita area is at the eastern end of the Ventura basin. The rock formations consist of a series of Tertiary and Quaternary marine and continental sediments dipping northwestward off the complex of very much older crystalline rocks that are exposed in the western San Gabriel Mountains only a mile southeast of producing wells. Unconformities separate most formations, and interfingering and intergradation of marine and continental beds is common, particularly in the upper Miocene Modelo formation (subsurface only, in western part of Placerita field), lower Pliocene Elsmere member of the Repetto formation, and upper Pliocene Upper Pico and Sunshine Ranch members of the Pico formation.

Structure. The structure of the area is dominated by the San Gabriel fault zone, a major series of steeply north-dipping (70° to 80°) shear planes that trend N. 65° W. and show right-lateral horizontal movement. Post-lower Pleistocene movement has been at least 1.5 miles, and movement since late Miocene time may have amounted to 15 or 20 miles. This fault separates two quite different geologic areas, and abruptly terminates the northward extension of the Placerita oil field. The eastward extension of the field is as sharply bounded by the north-trending Whitney fault. North of Whitney Canyon, well data suggest that the Whitney fault dips about 65° W. and that pre-Pliocene displacement was about 5,000 feet, the east block having moved relatively up. Saugus beds seem to have been little disturbed by the fault, the total Pliocene and post-Pliocene movement amounting to a maximum of about 150 feet, apparently opposite in sense to the pre-Pliocene movement.

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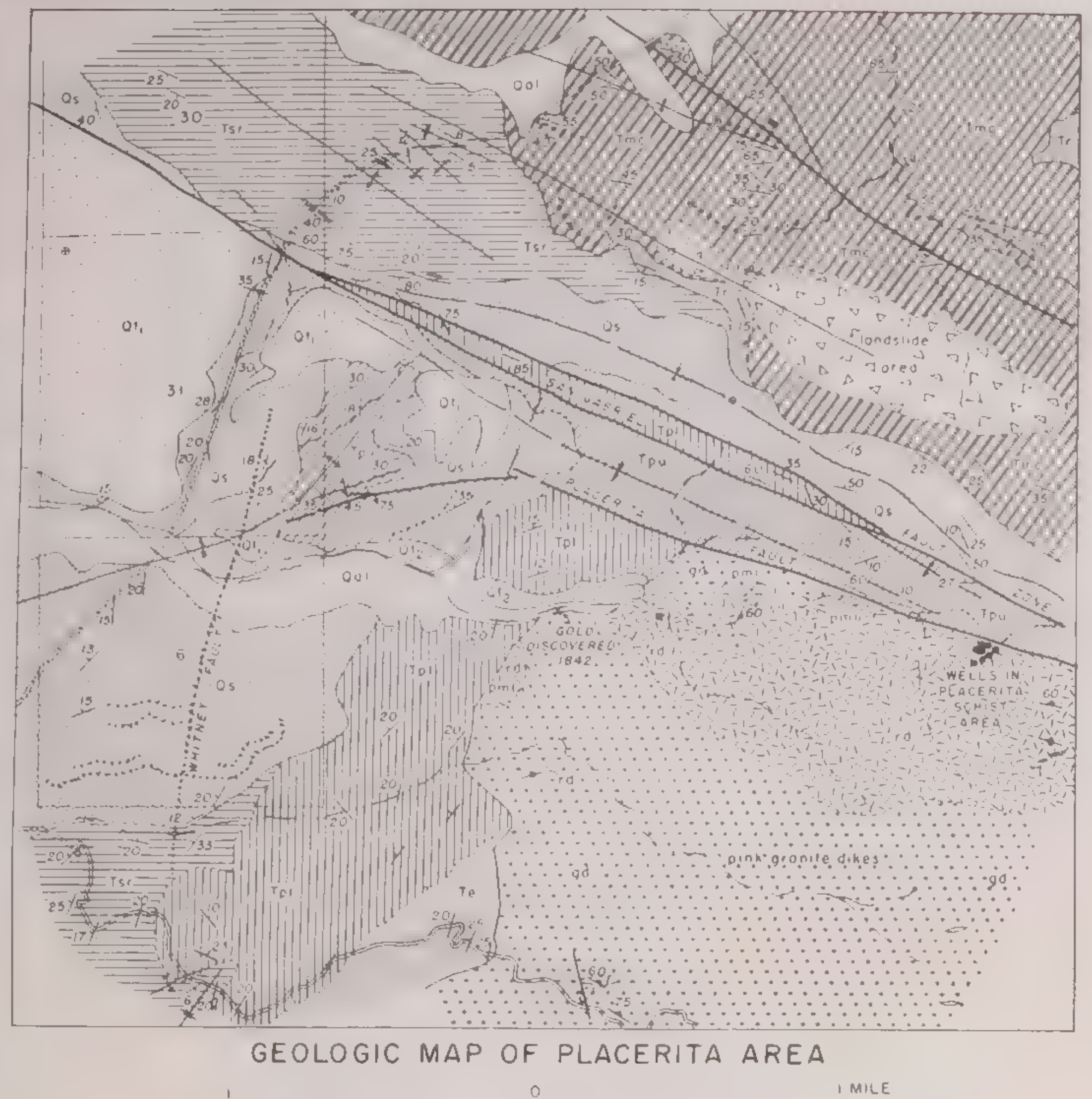
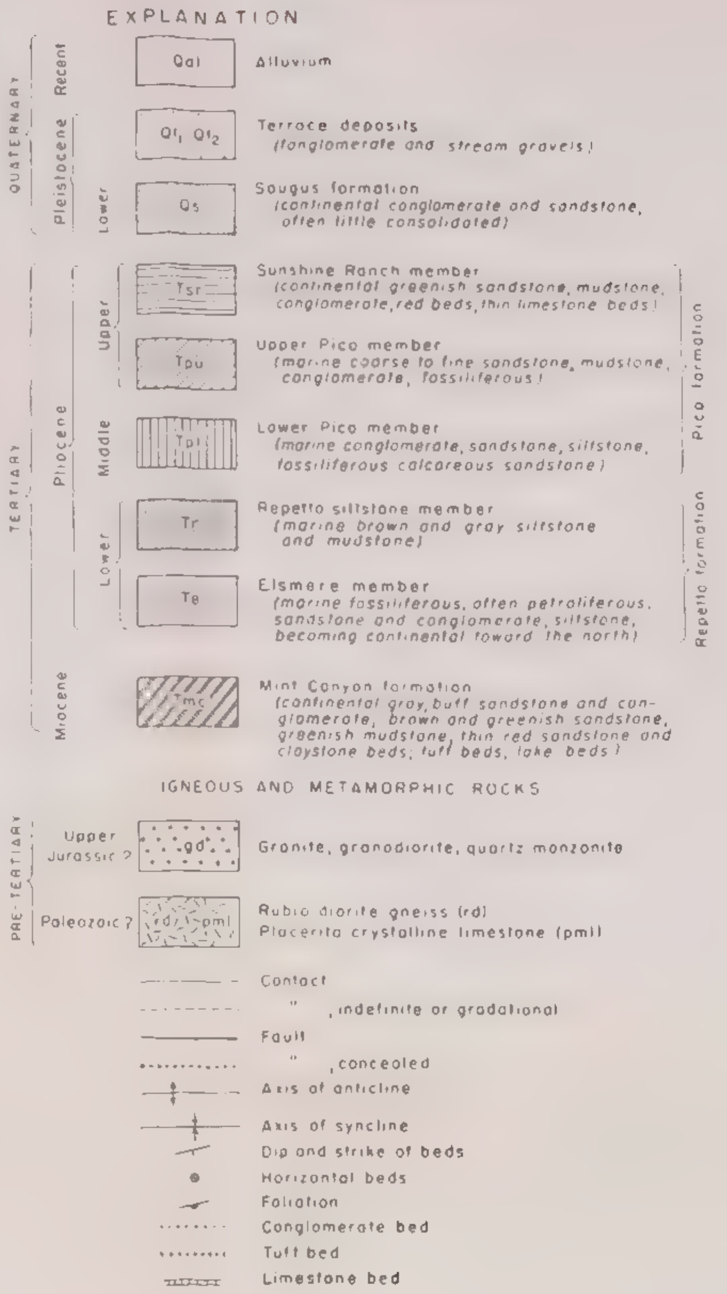
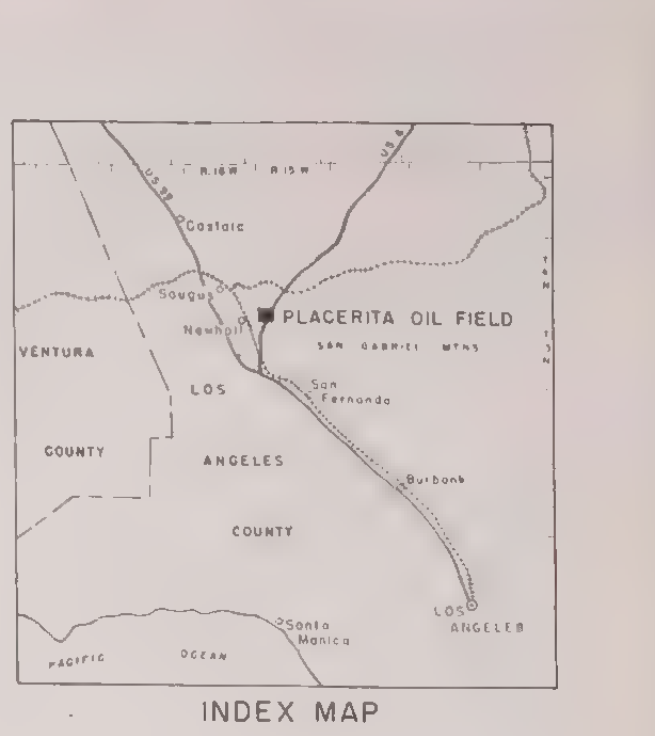
* Supervising Mining Geologist, California Division of Mines, San Francisco.

TN
24
C3
A3
no.1
c.3

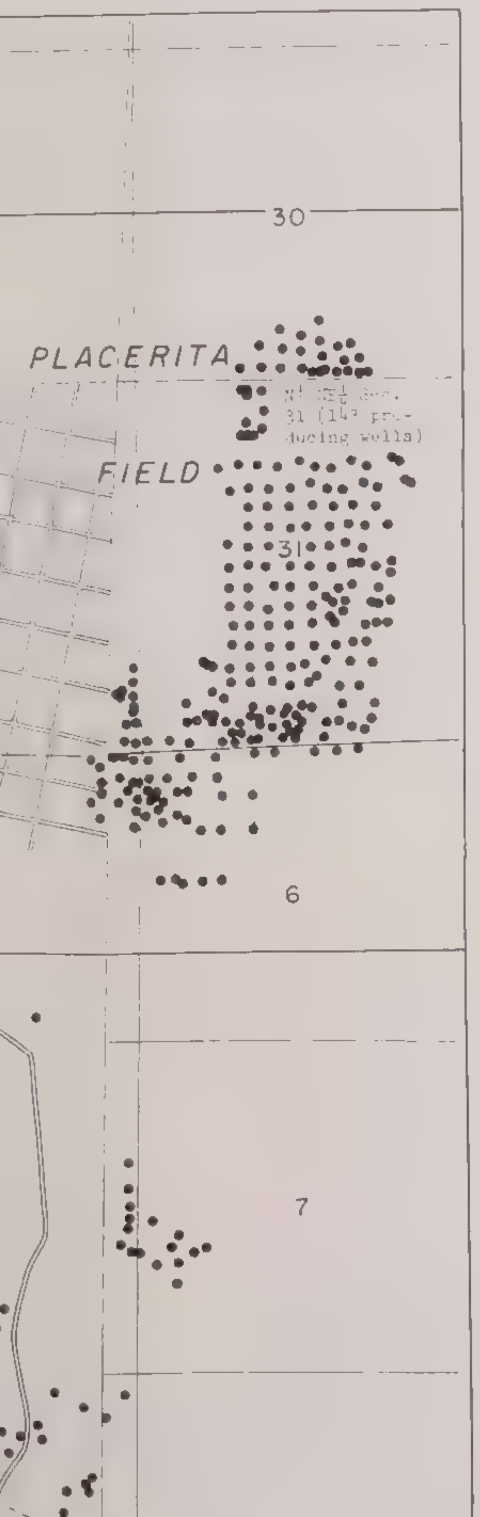


GEOLOGIC MAP OF PLACERITA AREA

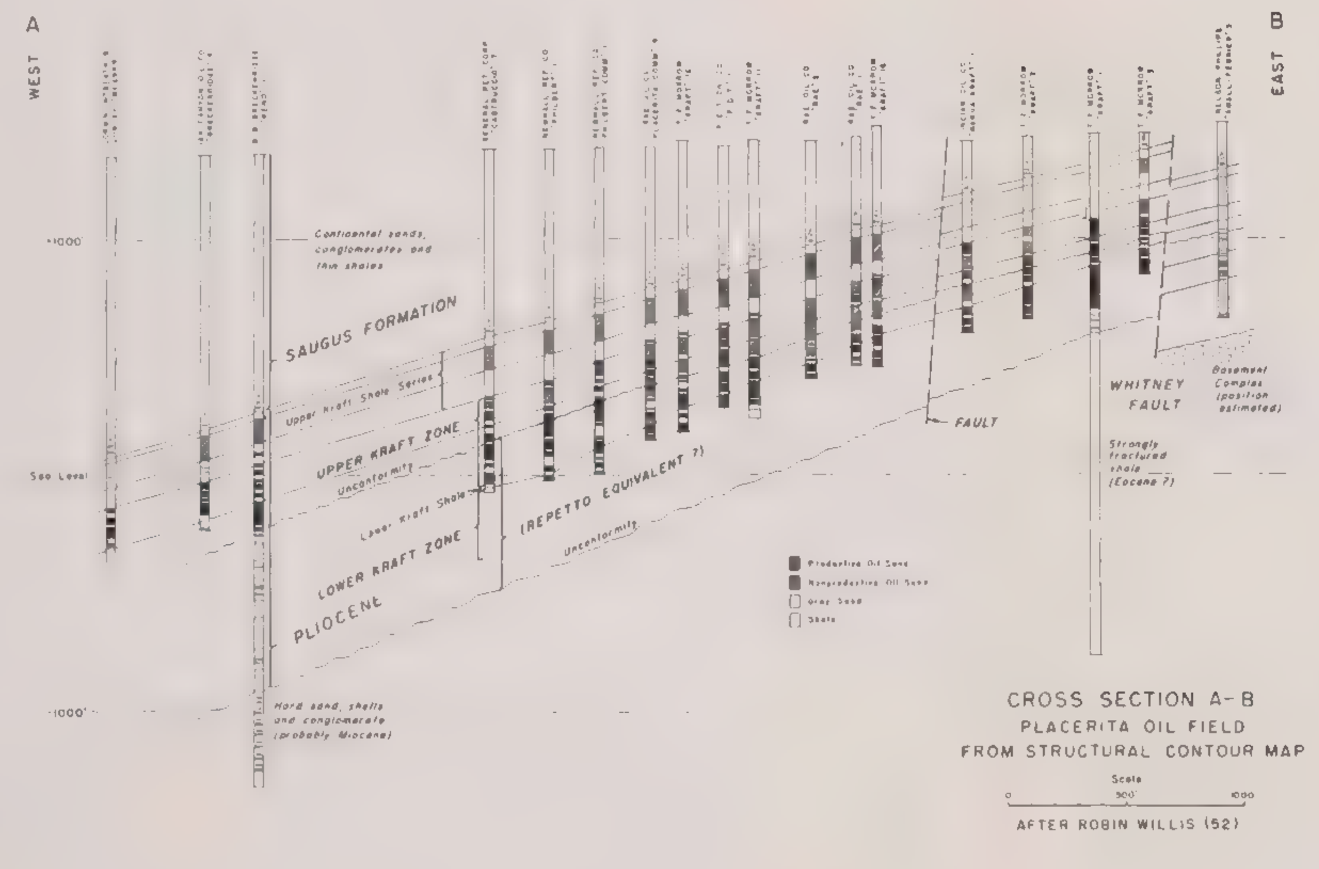

EXPLANATION
QUATERNARY
Recent
Pleistocene
Lower
Qal
Alluvium
Qt1 Qt2
Terrace deposits
(conglomerate and stream gravels)
Qs
Saugus formation
(continental conglomerate and sandstone, often little consolidated)
TERTIARY
Pliocene
Upper
Middle
Lower
Tsr
Sunshine Ranch member
(continental greenish sandstone, mudstone, conglomerate, red beds, thin limestone beds)
Tpu
Upper Pico member
(marine coarse to fine sandstone, mudstone, conglomerate, fossiliferous)
Tpl
Lower Pico member
(marine conglomerate, sandstone, siltstone, fossiliferous calcareous sandstone)
Pico formation
Tr
Repetto siltstone member
(marine brown and gray siltstone and mudstone)
Te
Elsmere member
(marine fossiliferous, often petroliferous, sandstone and conglomerate, siltstone, becoming continental toward the north)
Repetto formation
Miocene
Tmc
Mint Canyon formation
(continental gray, buff sandstone and conglomerate, brown and greenish sandstone, greenish mudstone, thin red sandstone and claystone beds; tuff beds, lake beds)
IGNEOUS AND METAMORPHIC ROCKS
PRE-TERTIARY
Upper Jurassic ?
gd
Granite, granodiorite, quartz monzonite
Paleozoic ?
rd pml
Rubio diorite gneiss (rd)
Placerita crystalline limestone (pml)
Contact
" , indefinite or gradational
Fault
" , concealed
Axis of anticline
Axis of syncline
Dip and strike of beds
Horizontal beds
Foliation
Conglomerate bed
Tuff bed
Limestone bed



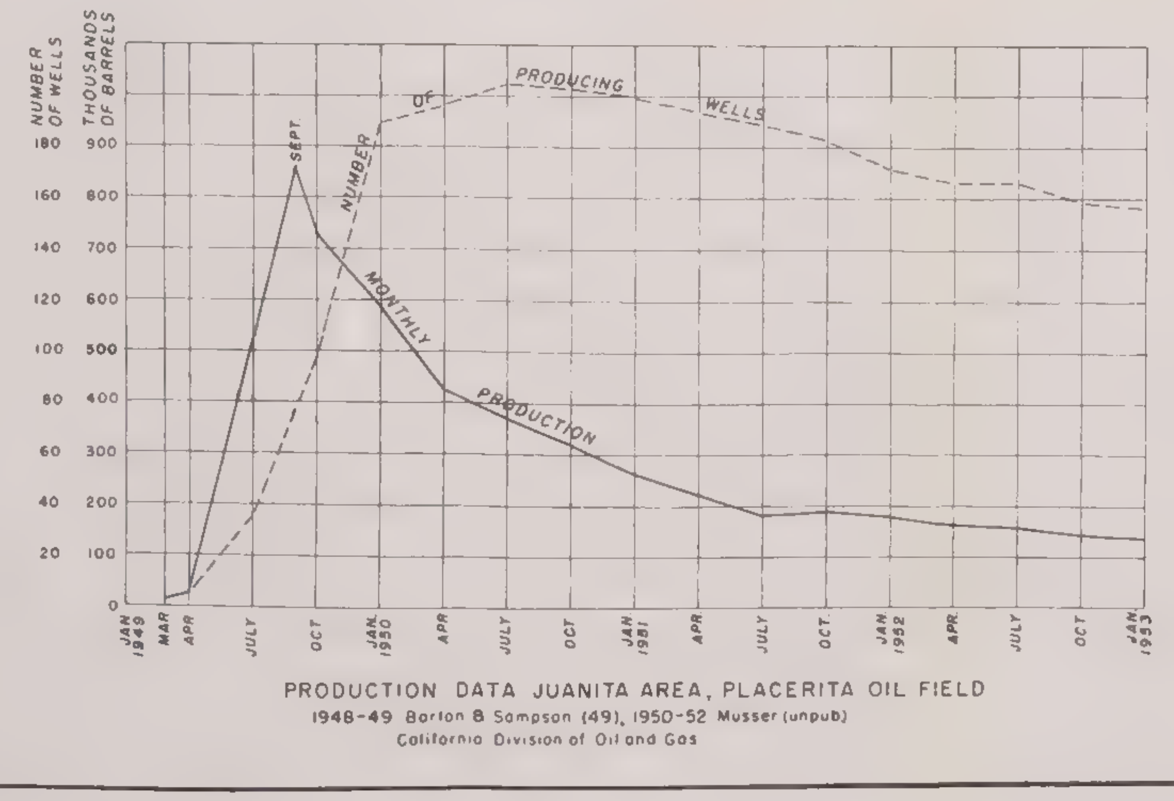
INDEX MAP



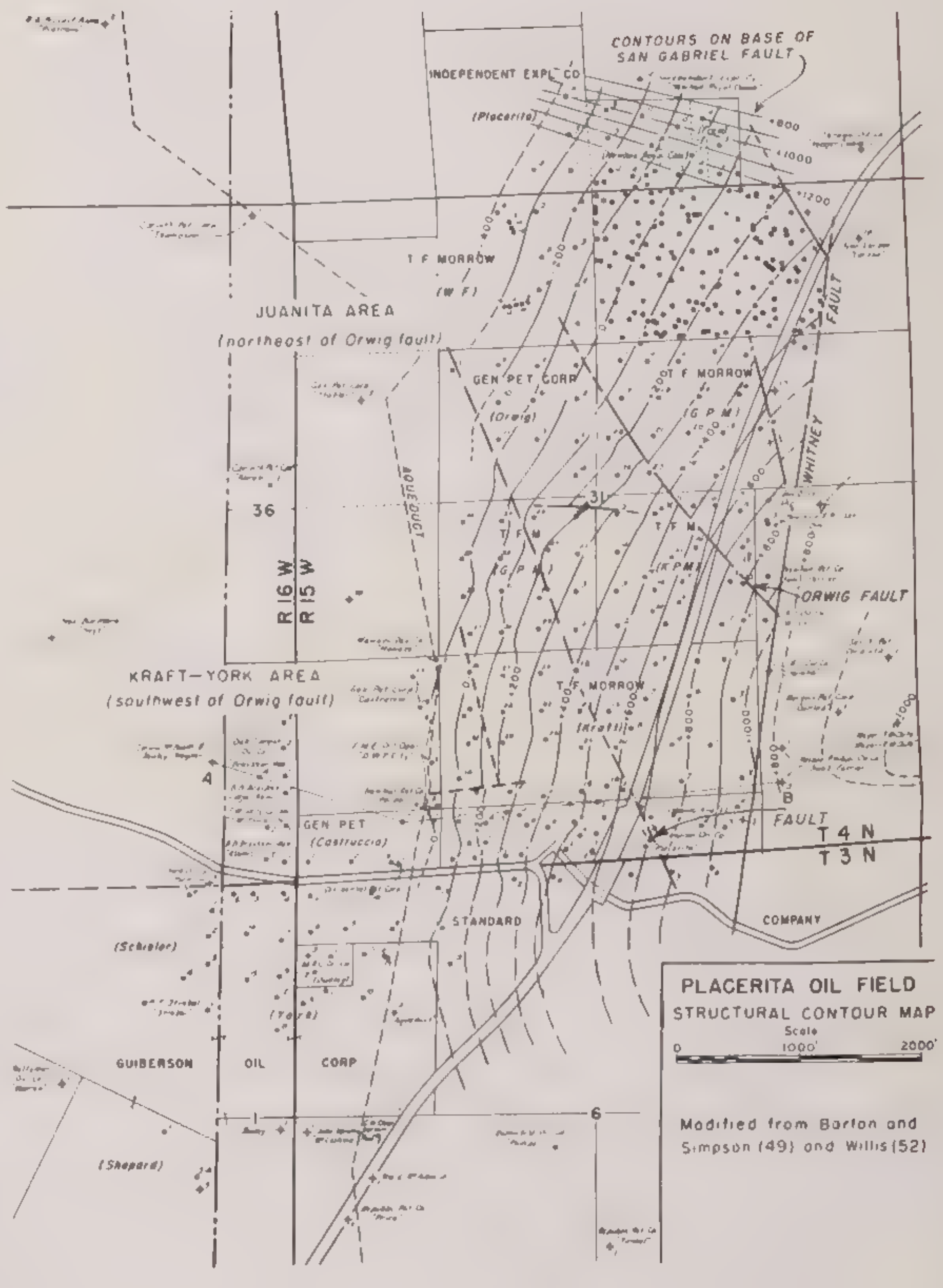
T NEWHALL OIL FIELD
L FIELD
L FIELD No 18A Revised Jan 1953,
F OIL AND GAS



CROSS SECTION A-B
PLACERITA OIL FIELD
FROM STRUCTURAL CONTOUR MAP
Scale
0 500 1000
AFTER ROBIN WILLIS (52)



PRODUCTION DATA JUANITA AREA, PLACERITA OIL FIELD
1948-49 Barton & Sampson (49), 1950-52 Musser (unpub)
California Division of Oil and Gas



PLACERITA OIL FIELD
STRUCTURAL CONTOUR MAP
Scale
0 1000' 2000'

Modified from Barton and Simpson (49) and Willis (52)

are exposed
east of pro-
and inter-
beds is com-
on (subsur-
ene Elsmere
Upper Pico

by the San
ing (70° to
lateral hori-
een at least
e amounted
ent geologic
sion of the
as sharply
of Whitney
bout 65° W.
et, the east
have been
ost-Pliocene
apparently

The author believes that the Whitney fault is a major left-lateral shear zone forming the boundary between the Upper Tertiary sediments of the eastern Ventura basin and the crystalline rocks of the San Gabriel Mountains. The Whitney fault may well represent the southerly extension of the Pole Canyon fault, which has been displaced approximately 2 miles in a right-lateral sense by post-Pliocene movement along the San Gabriel fault. Several minor faults have been discovered through well records, but they cannot be recognized on the surface. One of these, the Orwig normal fault, trends northwest across the center of the field and separates the Juanita area of high-gravity oil from the Kraft-York area of low-gravity oil. Another break, similar in trend and character to the Orwig fault and a quarter of a mile southwest of it, forms a local gravity barrier between two different low-gravity oils of the Kraft-York area.

The area as a whole is complexly folded and faulted, but structure contours on top of the Lower Kraft zone in the oil field show that the Pliocene beds dip essentially homoclinally 15° to 20° west-northwest. In the southern part of the Kraft-York area this dip is due west, whereas in the northern part of the Juanita area the dip is northwest. Surface attitudes in the Saugus gravels and older terrace deposits that cover the oil field are difficult to evaluate.

Production. The two producing zones in the field have been designated the Upper Kraft and the Lower Kraft. The Upper Kraft zone, in the middle to upper Pliocene Pico formation, ranges from 170 to 250 feet in thickness and is productive of 11° to 17° gravity oil in the Kraft-York area only. The zone is terminated at the west edge of the field by a bottom-water interface. Initial production was 25 to 175 barrels per well per day. The Lower Kraft zone, in the lower Pliocene Repetto formation, ranges from 300 to 450 feet in thickness and is productive of 20° to 25° gravity oil northeast of the Orwig fault in the Juanita area, and 12° to 16° oil in the Kraft-York area. Initial production from the Lower Kraft zone in the Juanita area was as high as 3,000 barrels per day from some wells, but declined rapidly.

Faulting has been of prime importance in the accumulation of oil in the Placerita field. The San Gabriel and Whitney fault zones form the north and east limits of accumulation of oil in the northwest-dipping Pliocene beds of the field. Faults of small displacement and no surface expression have separated the field into pools with oils of three different gravities. Folds and faults that trend roughly N. 70° E. in the southern part of the field probably are responsible for its southern boundary; bottom-water determines the western limits of the field. Up-dip lensing in the members of the Pico formation and unconformities at the base of the Saugus and Pico formations probably have also influenced accumulation. Wells drilled into Eocene and Paleocene formations in the field have been dry.

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Walling, R. W., 1934, Report on Newhall oil field: Summary of operations, California oil fields: California Div. Oil and Gas, vol. 20, pp. 50-58 (Elsmere area, pp. 38-43; Whitney Canyon area, pp. 43-46; Placerita Canyon area, pp. 46-50).

Willis, Robin, 1952, Placerita oil field: Am. Assoc. Petroleum Geologists Guidebook, Joint Annual Meeting, Los Angeles, Mar. 1952, pp. 32-41 (Subsurface geology; structural contour map, sections and electric logs).

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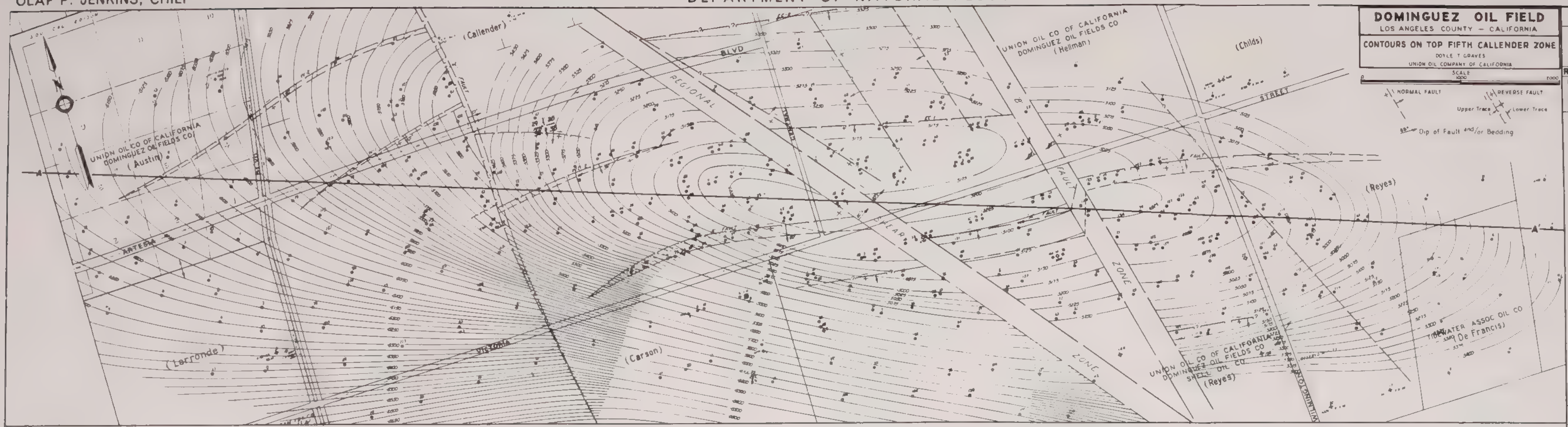
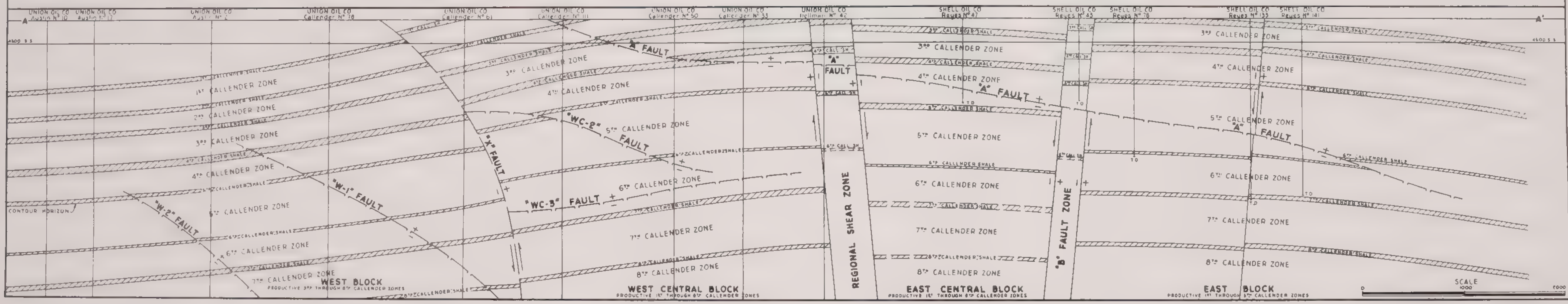
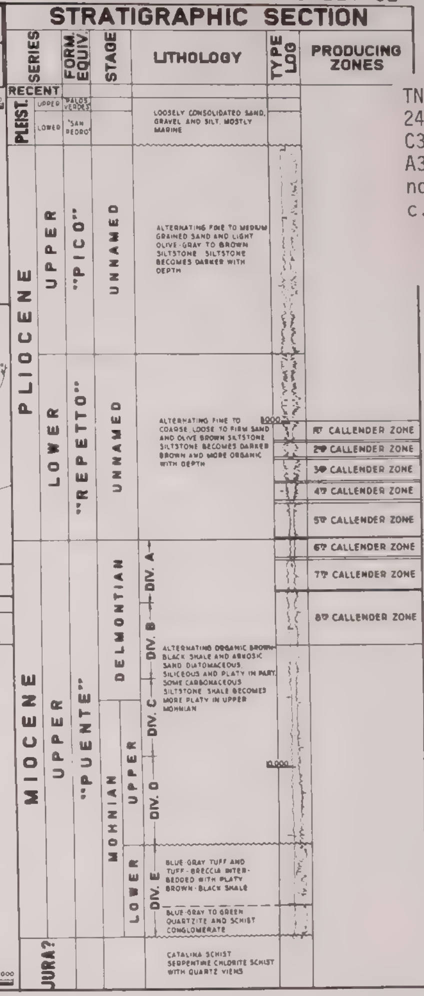
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 170 MAP SHEET 32

TN
24
C3
A3
no.17
c.3


DOMINGUEZ OIL FIELD
LOS ANGELES COUNTY – CALIFORNIA
CONTOURS ON TOP FIFTH CALLENDER ZONE
DOYLE T GRAVES
UNION OIL COMPANY OF CALIFORNIA
SCALE
0
1000
2000
NORMAL FAULT
REVERSE FAULT
Upper Trace
Lower Trace
Dip of Fault and/or Bedding
UNION OIL CO OF CALIFORNIA DOMINGUEZ OIL FIELDS CO (Austin)
(Callender)
UNION OIL CO OF CALIFORNIA DOMINGUEZ OIL FIELDS CO (Hellman)
(Childs)
(Reyes)
(Larronde)
(Carson)
UNION OIL CO OF CALIFORNIA DOMINGUEZ OIL FIELDS CO SHELL OIL CO (Reyes)
TIDEWATER ASSOC OIL CO (De Francis)
REGIONAL BLVD
ARTESIA
VICTORIA
STREET
FAULT ZONE
A
A'




STRATIGRAPHIC SECTION
SERIES
FORM. EQUIV.
STAGE
LITHOLOGY
TYPE LOG
PRODUCING ZONES
RECENT
PLEIST.
UPPER
LOWER
PALOS VERDES
"SAN PEDRO"
LOOSELY CONSOLIDATED SAND, GRAVEL AND SILT, MOSTLY MARINE
PLIOCENE
UPPER
"PICO"
UNNAMED
ALTERNATING FINE TO MEDIUM GRAINED SAND AND LIGHT OLIVE-GRAY TO BROWN SILTSTONE. SILTSTONE BECOMES DARKER WITH DEPTH
LOWER
"REPETTO"
UNNAMED
ALTERNATING FINE TO COARSE, LOOSE TO FIRM SAND AND OLIVE BROWN SILTSTONE. SILTSTONE BECOMES DARKER BROWN AND MORE ORGANIC WITH DEPTH
5000
1st CALLENDER ZONE
2nd CALLENDER ZONE
3rd CALLENDER ZONE
4th CALLENDER ZONE
5th CALLENDER ZONE
6th CALLENDER ZONE
7th CALLENDER ZONE
8th CALLENDER ZONE
MIOCENE
UPPER
"PUENTE"
DELMONTIAN
MOHNIAN
UPPER
LOWER
DIV. A
DIV. B
DIV. C
DIV. D
DIV. E
ALTERNATING ORGANIC BROWN-BLACK SHALE AND ARKOSIC SAND DIATOMACEOUS, SILICEOUS AND PLATY IN PART, SOME CARBONACEOUS SILTSTONE. SHALE BECOMES MORE PLATY IN UPPER MOHNIAN
10,000
BLUE-GRAY TUFF AND TUFF-BRECCIA INTERBEDDED WITH PLATY BROWN-BLACK SHALE
BLUE-GRAY TO GREEN QUARTZITE AND SCHIST CONGLOMERATE
JURA?
CATALINA SCHIST SERPENTINE CHLORITE SCHIST WITH QUARTZ VIENS

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET NO. 32

GEOLOGY OF THE DOMINGUEZ OIL FIELD, LOS ANGELES COUNTY

By Doyle T. Graves *

General Features. The Dominguez oil field, one of the principal fields of the Newport-Inglewood uplift, is 12 miles south of the center of the city of Los Angeles and 2½ miles southwest of the city of Compton. The field is located on Dominguez Hill, the topography of which reflects in a general way the structure of the underlying Tertiary strata. Exploratory drilling on Dominguez Hill was begun in 1916 and was continued until 1923, when the Union Oil Company of California discovered the field with the completion of Callender No. 1A. Since this time, nearly 500 wells have been drilled, 350 of which currently are producing an aggregate 11,000 barrels per day. Oil recovered in this field to date totals nearly 200,000,000 barrels.

Stratigraphy. Approximately 11,000 feet of sediments overlie the schist of the basement complex at Dominguez. These include, from youngest to oldest, the subsurface equivalents of the Palos Verdes and San Pedro formations of Pleistocene age, the Pico and Repetto formations of Pliocene age, and the Puente formation of late Miocene age.

The Pleistocene beds are approximately 600 feet thick, and consist of loosely consolidated sands, gravels, and silts. The contact between the upper Pleistocene Palos Verdes formation and the lower Pleistocene San Pedro formation is known to be unconformable in surface exposures along the Newport-Inglewood uplift.

The upper Pliocene section (Pico equivalent) consists of alternating beds of sands, sandy shales, and silts, and is approximately 2,200 feet thick. The sands generally are fine- to medium-grained, soft, and friable. The shales and silts range in color from light olive-gray to brown. The darker colors are more characteristic of the lower parts of the formation. The contact with the overlying San Pedro formation has not been cored from the subsurface at Dominguez, but in the Seal Beach oil field, approximately 9 miles to the southeast, it has been cored and is known to be unconformable on the basis of foraminiferal data. It therefore is assumed that the contact between the Pleistocene and Pliocene sections is also unconformable at Dominguez. No production is obtained from the upper Pliocene beds at Dominguez.

The lower Pliocene strata (correlative with the Repetto type section) are conformable beneath those of the Pico formation, and attain an average thickness of approximately 2,800 feet. This section consists of alternating fine to coarse, loose to medium-hard sandstone, shale, sandy shale, and siltstone. In general the shale beds range in color from olive to dark brown, and become finer textured, darker colored, and more organic in the lower parts of the formation. Five producing zones, the First through the Fifth Callender, have been developed within the lower Pliocene section.

The Puente formation, of late Miocene age, has been classified into five major foraminiferal divisions (A, B, C, D, and E) in the Los Angeles basin by Stanley G. Wissler and Bradford C. Jones of the Union Oil Company. Beds representing Divisions A, B, C, and D (Delmontian and upper Mohnian stages of Kleinpell) are lithologically very similar at Dominguez. Beds of these four divisions lie conformably beneath the lower Pliocene beds, and have an average total thickness of 4,300 feet. They consist of alternating shale, sandy shale, and sandstone, with minor amounts of micaceous and carbonaceous siltstone. The shale beds generally are dark brown to brownish black, and some streaks contain sufficient diatomaceous material to give them a tannish cast. They commonly are well indurated, and many zones are siliceous and platy. The sandstone beds range from fine- to medium-grained, and from soft to hard. Three Miocene producing horizons (the 6th, 7th, 8th Callender zones) occur in Divisions A and B. No commercial production has been developed at Dominguez from beds below those of Division B.

Strata of Division E (Lower Mohnian) lie unconformably beneath the Division-D strata. The Division-E section, as encountered in Union Oil Company well Callender No. 79, consists of approximately 700 feet of hard, blue-gray volcanic tuff and tuff-breccia with interbedded brittle, platy, brownish black shale that contains fish scales believed to be of lower Mohnian age. Foraminifera restricted to the lower Mohnian were found in this same stratigraphic interval in Hellman No. 58. The volcanic series is underlain by approximately 400 feet of hard, blue-gray to green quartzite- and schist-bearing conglomerate. The basement complex that lies unconformably beneath this conglomerate is a serpentine-chlorite schist, believed to be a correlative of the Franciscan (Jurassic?) group. The only well penetrating the schist at Dominguez, Callender No. 79, has yielded cores described as soft, predominantly greenish and grayish schist, with local brick-red streaks, numerous injected quartz veins, and small amounts of talc.

Structure. The Dominguez oil field is situated on a northwest-striking anticlinal structure that occupies a position along the Newport-Inglewood line of folds. In general, folds along this uplift appear to be the result of right-lateral shearing movements between blocks of the underlying basement rocks, in which the southwesterly blocks moved horizontally northwestward relative to the northeasterly blocks. However, the Dominguez fold presents two interesting exceptions to the generalities that have been applied to the Newport-Inglewood uplift: (1) movement along the Regional shear zone of Dominguez (thought to be a member of the Newport-Inglewood shear zone system) appears to have been left-lateral rather than right-lateral; and (2) the axis of the Dominguez fold is not parallel to the axes of the major structures in the adjacent fields (Rosecrans and Long Beach), but rather is parallel to the Playa del Rey-El Segundo-Lawndale-Alondra Park trend. These exceptional features are possibly results of alternating movements along the Newport-Inglewood shear zone and the north-dipping thrust zone on the south flank of the Dominguez structure. This low-angle thrust fault strikes parallel to the Playa del Rey-Alondra Park trend, and possibly represents an extension of a zone of weakness associated with the pre-Miocene buried ridge that has been encountered from Playa del Rey to Alondra Park.

The anticlinal structure of the Dominguez field has been distorted by a complex system of faults that become progressively more strongly developed with depth. Three major faults, the Regional shear zone, the ''B'' fault zone, and the ''X'' fault, divide the field into four major structural blocks, the West, the West-Central, the East-Central, and the East block. Several south-dipping reverse faults further divide the field into smaller blocks. The most significant of these reverse faults is the ''A'' fault, which persists in three of the major structural blocks and apparently is related directly to movement along the Newport-Inglewood system. The other reverse faults appear to branch from one of the major faults, and do not transect major blocks. The fault feature of greatest interest at Dominguez is a north-dipping zone of thrusting that strikes parallel to the axis of the fold, and is encountered in the Miocene strata on the south flank of the fold. Movements along this thrust fault appear not to be related directly to the Newport-Inglewood uplift, and the fault has been offset by the Regional shear zone in a left-lateral direction.

Faulting has influenced the accumulation of oil in this field to a considerable degree. Most faults with displacements in excess of 15 feet appear to have been barriers to accumulation, and have divided the field into more than 35 fault-block pools with different oil-water interfaces, slightly different gravities, and different pressures.

The author wishes to thank W. S. Eggleston, Chief Petroleum Engineer for the Union Oil Company of California, for permission to publish the data appearing here.

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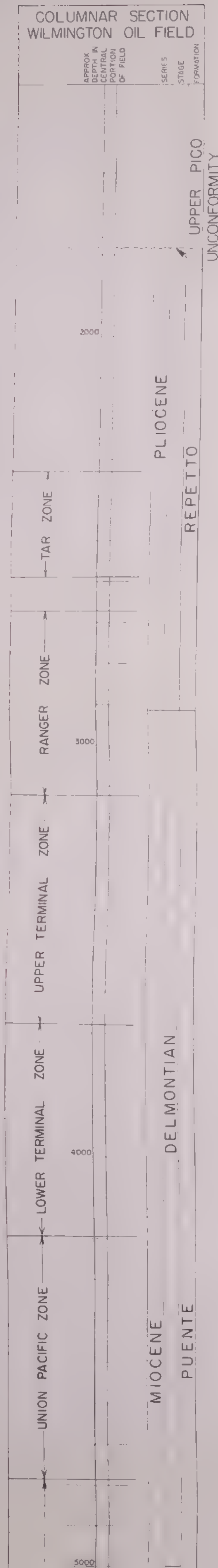
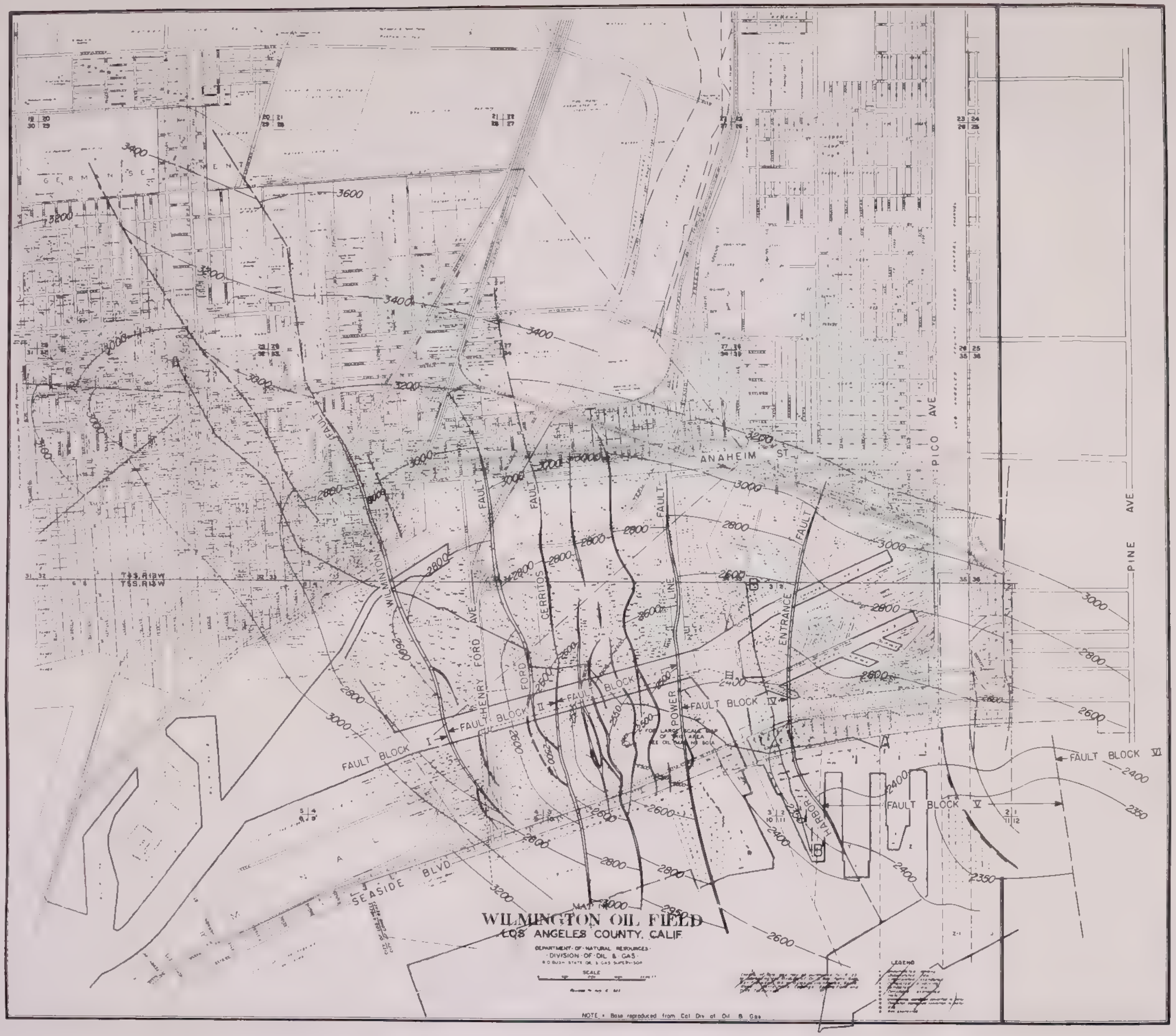
COLUMNAR SECTION
WILMINGTON OIL FIELD

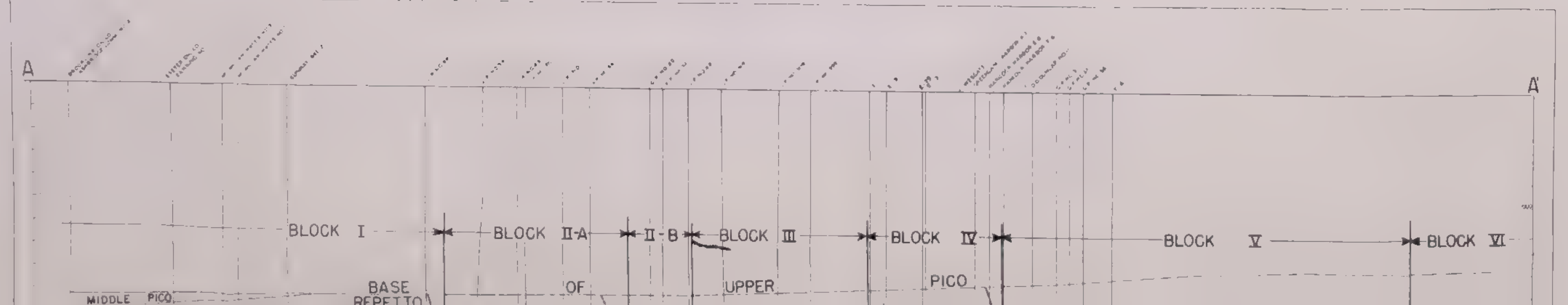


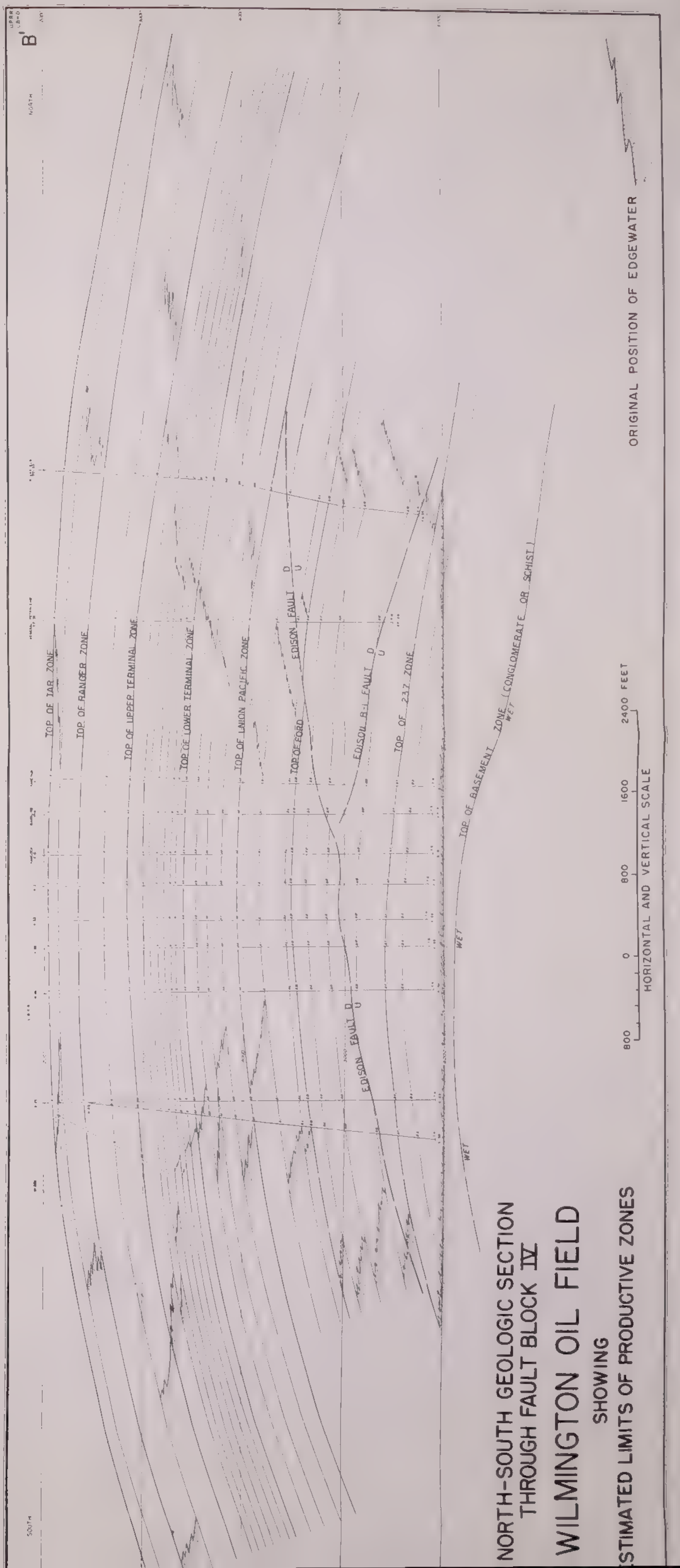


WILMINGTON OIL FIELD
STRUCTURAL CONTOURS ON TOP OF RANGER ZONE

Compiled from maps by UNION PACIFIC RAILROAD CO.,
LONG BEACH OIL DEV. CO., DIV. O.&G. REPORT by W.J.Crown.

Base map by CALIFORNIA STATE DIVISION OF OIL AND GAS

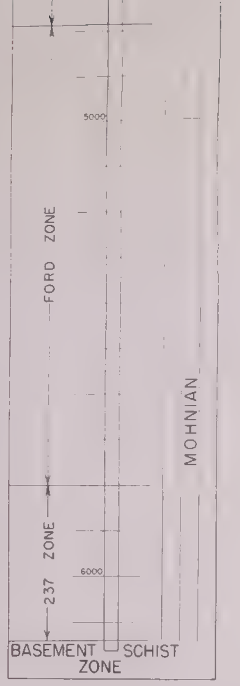


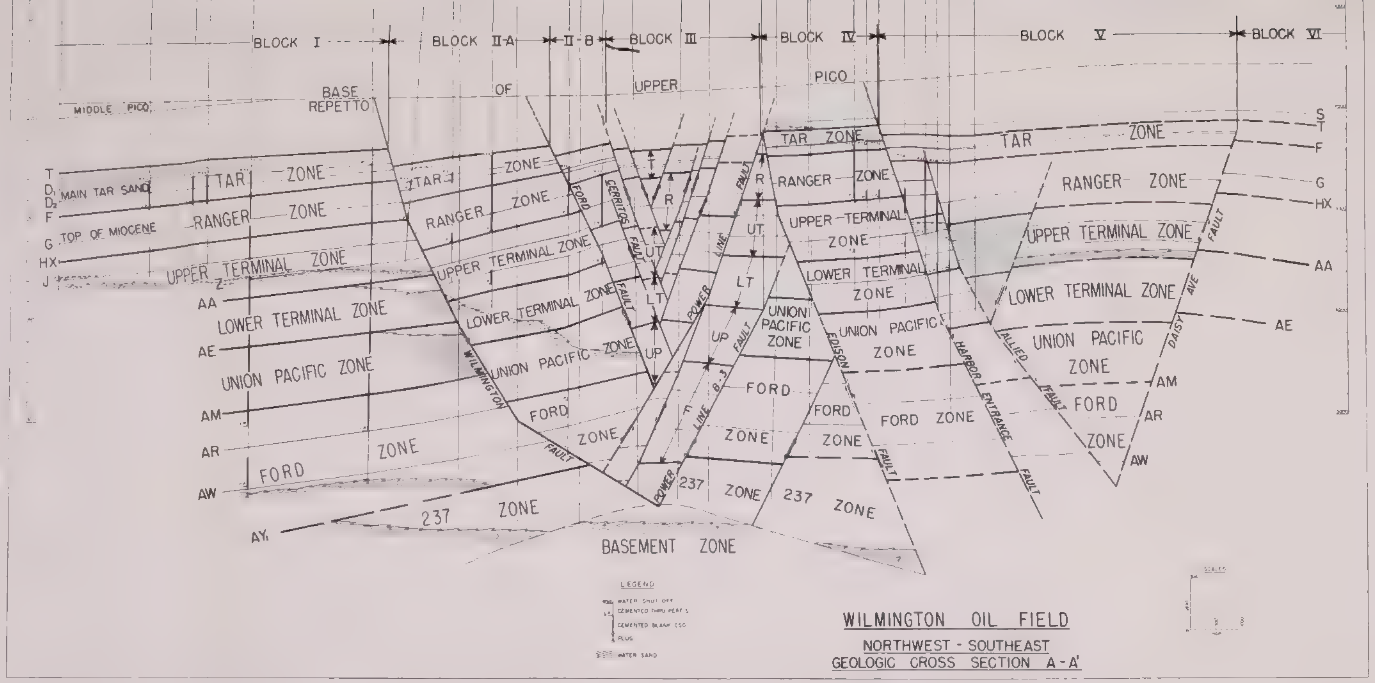

B'
NORTH
SOUTH
ORIGINAL POSITION OF EDGEWATER
TOP OF TAR ZONE
TOP OF RANGER ZONE
TOP OF UPPER TERMINAL ZONE
TOP OF LOWER TERMINAL ZONE
TOP OF UNION PACIFIC ZONE
TOP OF FORD
EDISON FAULT
EDISON B-1 FAULT
TOP OF 237 ZONE
TOP OF BASEMENT ZONE (CONGLOMERATE OR SCHIST)
D
U
WET
HORIZONTAL AND VERTICAL SCALE
800
0
800
1600
2400 FEET

NORTH-SOUTH GEOLOGIC SECTION
THROUGH FAULT BLOCK IV

WILMINGTON OIL FIELD

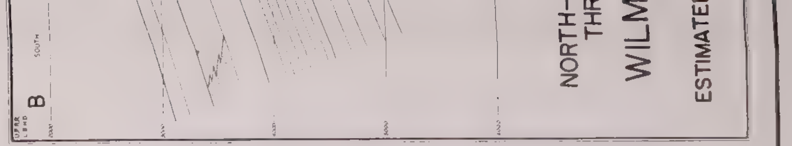
SHOWING
ESTIMATED LIMITS OF PRODUCTIVE ZONES





WILMINGTON OIL FIELD

NORTHWEST - SOUTHEAST
GEOLOGIC CROSS SECTION A-A'



DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 33

GEOLOGY OF THE WILMINGTON OIL FIELD, LOS ANGELES COUNTY

By Read Winterburn *

History and Production. The Wilmington oil field extends from the center of the city of Wilmington well into the city of Long Beach and into the offshore area south of the main business district of Long Beach.

Commercially attractive accumulation was first proved in this field December 6, 1936, by the completion of General Petroleum Corporation well Terminal No. 1 in the interval 3,122 feet to 3,625 feet at an initial rate of 1,389 barrels per day of 20.5 gravity oil. This well was located after a thorough seismographic survey had been made of the area. It encountered Jurassic (?) schist at 6,787 feet, was drilled to a total depth of 6,814 feet, and then was plugged back to the zone of completion.

Completion of Terminal No. 1 initiated an intensive campaign of drilling that has resulted in the completion of approximately 2,650 wells during two principal periods. Activities of the first period, which involved the development of the zones down to and including the Terminal zone, reached a peak in 1940 and have continued at a reduced rate since then. The second period involved the drilling of wells to the deeper Ford, 237, and Schist zones from 1943 to 1948. Development has continued during recent years as a result of extention of the field to the southeast, the drilling of infilling wells in the older part of the field, and the replacement of wells that have been irreparably damaged by earth movements.

Unique problems of development have been presented by major subsidence in the field, which has necessitated construction of numerous dikes and the building up of the surface by earth fill in order to keep out water from the nearby ocean and navigation channels. Localized subsurface slippages, which have sheared well casings above a depth of 2,000 feet, have caused the loss of several hundred wells and have occasioned a vigorous program of replacement drilling. The excellent rates of production obtained from the replacement wells, as compared to the old wells, are to a great extent responsible for maintaining the field production rate at a high level during the past three years.

Directional drilling has been used extensively in this field because much of the area overlying the productive oil zones is under water or is occupied by buildings and other surface installations. Wells have been deflected as much as 4,000 feet horizontally to reach productive sands at a vertical depth of slightly more than 3,000 feet.

Accumulative production from the field to June 30, 1953, is about 628,000,000 barrels, and the present rate of production is 125,000 barrels per day. The all-time production peak of about 143,000 barrels per day was reached early in 1951.

Stratigraphy. The table in third column shows the various formations encountered in the Wilmington field.

Very little coring has been done in the upper 2,000 feet of the section, so that the exact top of the upper Pico beds and the areal extent of the middle Pico beds have not been determined. The middle Pico strata apparently are overlapped in the northern part of the field, but it is possible that a thin section of these strata extends across the top of the structure.

Productive Zones. Seven productive zones are recognized in the Wilmington field (see sections). From top to bottom these are:

1. Tar zone, between electrical markers T and F. Thickness ranges from 250 to 400 feet; average 40 percent sand; gravity of oil 12 to 15 degrees A.P.I.

Formation	Age	Thickness (feet)	Lighology and remarks
San Pedro......	Quaternary	1,000±	Fresh-water sands, gravels, and clays.
Upper Pico.....	Pliocene	800±	Alternating sandstones and siltstones.
Middle Pico....	Pliocene	0–200	Sandstones and siltstones.
		Unconformity	
Repetto........	Pliocene	875–1,150	Gray and green shales, siltstones, and sandstones at top, grading to interbedded grayish-brown shales and fine-grained sandstones toward bottom.
Puente.........	Miocene	4,100±	Hard brown shales and sandstones, sandstones are fine and unconsolidated at top, becoming firmer and coarser grained toward bottom. Top part contains layers of laminated diatomaceous shale.
		Unconformity	
Basement rocks.	Jurassic?		Schist overlain by hard, cemented conglomerate.

2. Ranger zone, between electrical markers F and HX. Thickness ranges from 400 to 600 feet; 15 to 30 percent sand; gravity of oil 12 to 25 degrees A.P.I.

3. Terminal zone, between electrical markers HX and AE. Thickness is about 1,100 feet; 50 to 70 percent oil sand; divided into upper and lower units for production purposes—gravity of oil in upper 400 feet 14 to 25 degrees and in lower part of zone 26 to 31 degrees A.P.I. The actual point of division in the zone ranges from 400 to 600 feet below the top in different wells.

4. Union Pacific zone, between markers AE and AL. Thickness is approximately 475 feet; about 20 percent oil sand; gravity of oil 28 to 32 degrees A.P.I.

5. Ford zone, between markers AM and AY. Thickness is approximately 950 feet; 25 to 35 percent oil sand; gravity of oil 28 to 32 degrees A.P.I. The entire 950-foot interval is not included in any one well, but thickness represents the interval from highest shutoff point to deepest penetration.

6. 237 zone, which includes all of the productive interval between AY₁ marker and the top of the basement. Thickness is approximately 350 feet; 25 to 50 percent oil sand; gravity of oil 28 to 32 degrees A.P.I.

7. Basement zone, which consists of fractured schist and the hard, cemented schist-bearing conglomerate that overlies the schist in some places. Maximum penetration in the Basement zone is 313 feet, and gravity of the oil produced is about 30 degrees A.P.I. The oil in this zone occurs entirely in fractures in the otherwise impermeable rocks.

Production from the basement rocks has been spotty, owing probably to variations in the degree and continuity of fracturing. Some wells were completed with high initial capacities and rapidly developed very high water cuts, the pressure remaining high after withdrawal of large volumes of oil and water. In other wells the pressure has been greatly reduced by the production of oil without a particularly large production of water. The total production from the Basement zone is a relatively small percentage of the total production from the field.

Structure. As shown on the accompanying structure contour map, the Wilmington field is located on a well-developed anticline. Five main faults, which trend north, or transverse to the axis of the fold, divide the field into six major structural blocks. For convenience of reference, these blocks are numbered consecutively from west to east on the map. They are most simply defined in the part of the section that includes the top four zones, whereas in some places at lower levels other faults form the boundaries between the principal blocks. This is particularly true in the case of Blocks III and IV below the intersection of the east-hading Ford fault and the west-hading Power Line fault (see section A-A').

All of the faults are normal, and, with the exception of the Power Line fault and minor parallel faults adjacent to it, they hade to the east.

The thickness of the Repetto (Pliocene) beds increases to a marked degree down the dip, and a much thicker Repetto section is present in the downthrown fault blocks than in the immediately adjacent upthrown blocks. This thickening of intervals in the downthrown fault blocks is accompanied by progressive increase in vertical displacement on the faults with depth down to the top of the Miocene Puente formation. Below this the displacement remains relatively constant, and stratigraphic intervals in the Miocene section are much more nearly uniform throughout the field.

The relation between thickness of the Repetto section and the structural features suggests that folding and faulting occurred concomitantly during deposition of the Repetto beds, which attained varying thicknesses depending on the relative amount of depression of the different areas during deposition. The folding and faulting in the Puente and Repetto beds are not reflected in the younger Pliocene and Quaternary beds.

The faults apparently are sealed, and they act as barriers to the movement of fluid. As a result, each of the six structural blocks is distinguished by oil of different gravity and by a distribution of edgewater and intermediate edgewater which is much different from that on other blocks. At many places water sands on one side of the fault are in contact with oil sands on the other side.

Type of Oil. The gravity of Wilmington crude oil ranges from 13 to 32 degrees A. P. I. Oil below 17 degrees gravity contains from 1.7 to 2.5 percent of sulfur. The sulfur content decreases with increase in gravity, and ranges from 0.6 to 0.9 percent for oil of 29 degrees gravity. Gasoline content ranges from 8 percent for 16-gravity oil to 31 percent for 29-gravity oil.

Within a given structural block, the oil of highest gravity in each zone is found at the highest structural position. This variation of gravity with structure is particularly pronounced in the Upper Terminal zone. The maximum difference occurs in Block IIA, where the Upper Terminal zone at the crest of the block yields oil of 25 degrees gravity, and wells in the lowest structural positions produce oil of about 13 degrees gravity.

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* Chief Petroleum Engineer, Union Pacific Railroad Company.

DIVISION OF MINES
OLAF P. JENKINS, CHIEF

STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

BULLETIN 170 M.S. 34

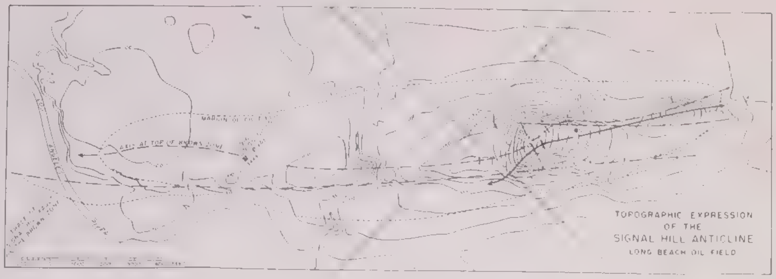

Figure 2

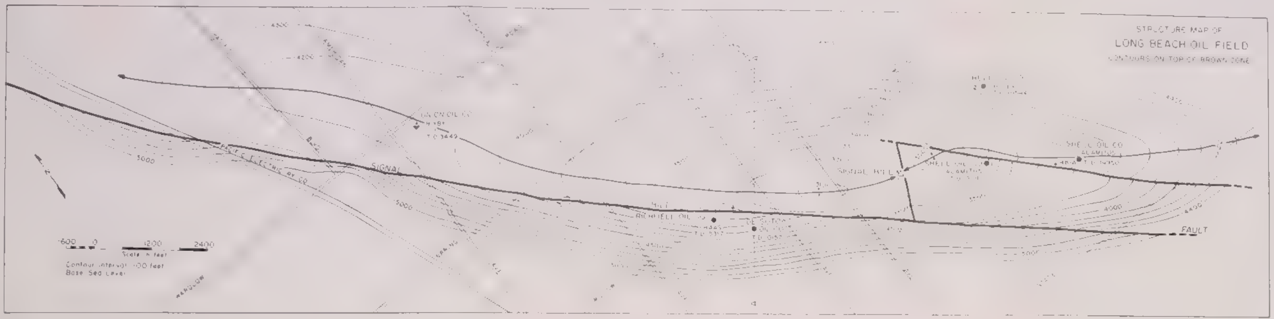

Figure 4

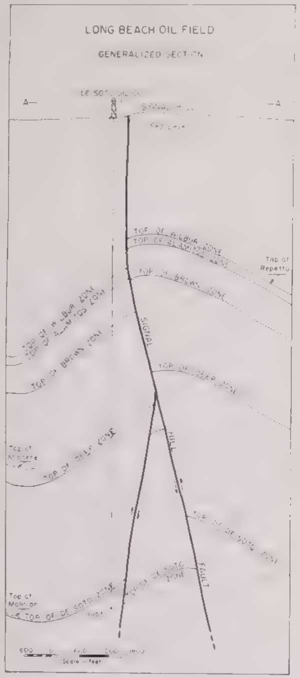

Figure 5

FIGURE 1 Aerial view northeastward across Long Beach, showing the Long Beach oil field and the San Gabriel Mountains in the distance.
Photograph ([illegible]) by Courtesy of Pacific Air Industries

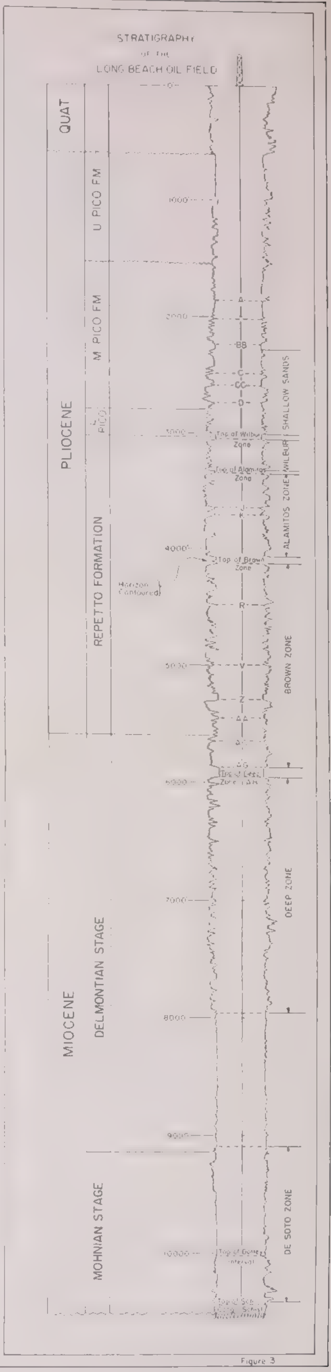

Figure 3

DIVISION OF MINES
BULLETIN 170
GEOLOGY OF SOUTHERN CALIFORNIA

MAP SHEET No. 34

GEOLOGY OF THE LONG BEACH OIL FIELD, LOS ANGELES COUNTY

By Paul H. Dudley*

The Long Beach oil field is located approximately 20 miles south of Los Angeles. It has produced more than 773,777,000 barrels of oil by January 1, 1954, and on this basis it ranks as the second largest oil field in the State. The oil zones are within strata of early Pliocene and late Miocene age, and are so numerous and prolific that total production of the field has amounted to more than 475,000 barrels per acre to date. Peak production, which was in 1923, averaged 188,522 barrels per day, and production 30 years later averaged 20,000 barrels per day. The gravity of the oil, which is asphalt-base, ranges from 16 to 32 degrees and averages 27 degrees.

The field, like others discovered about the same time in California, was suggested first by the physiography of the area. It is located under a 5-mile-long topographic high that trends northwestward and culminates in Signal Hill, which rises more than 300 feet above the adjacent coastal plain (see map). A pronounced linear scarp along the southwest flank reflects faulting (the Signal Hill fault), and a water gap that has been cut across the elongate high by an antecedent stream reflects uplift.

The Union Oil Company of California decided to explore the high in 1916, and located its No. "Bixby" 1 on the northwestern part. The well was drilled to 3,449 feet and was abandoned in sands near the top of what later was named the Alamitos zone. Unfortunately, production in this locality is not obtained above the Brown zone. If drilling had been continued 800 feet more, the test would have reached this zone and would have discovered the field.

Five years later the Shell Oil Company started its No. "Alamitos" 1 on the southeast slope of Signal Hill. This well was located on the basis of geologic mapping, which proved that the topographic high does reflect anticlinal folding. The axis could be traced only throughout the southeastern third of the high, the apex of the fold being Signal Hill itself. The southwest flank of the fold was noticeably steeper than the northeast flank, a feature corroborated later on by subsurface data. The plunge of the fold toward the northwest suggested that production would not extend far behind Signal Hill, and thus would be confined to the area in which the axis was mapped. The latter presumption has been proved incorrect by subsequent development of the field.

Shell Oil Company's No. "Alamitos" 1 came in as the discovery well of the field on June 25, 1921, and the producing sands were named the Alamitos zone (see sections). Shortly afterward, exploration near the crest of Signal Hill resulted in discovery of a higher productive zone at the top of the Repetto formation (Pliocene). This was named the Wilbur zone, and sometimes is referred to as the Lower Wilbur zone. The Brown and Deep zones then were found in turn. The Brown includes sands in the lower half of the Repetto formation and the uppermost part of the Miocene section, and the Deep embraces underlying sands in the upper Miocene section (Delmontian). These are the two most important and widespread zones of the field. In the course of their discovery the boundaries of the field were expanded rapidly in rather irregular fashion, as detailed elsewhere in the published record (Stolz, 1943). Production has been obtained locally along the southwest side of the Signal Hill fault (also known as the Cherry Hill fault) from several sands above the Wilbur zone. The oil in these has migrated upward along the fault from older beds, and thus they are not true producing zones. They have been given various names individually, but collectively they have been referred to as the Upper Wilbur zone.

Nearly three-quarters of the present areal extent of the field was known by the end of 1922, and the outline of its northwest end was established by 1925. A northwest extension of production along the southwest side of the Signal Hill fault was discovered in 1936.

Exploration within the field since it was outlined has been carried to deeper and deeper levels. The first important deep campaign was started in 1927 by the Richfield Oil Company with the drilling of No. "Haas" 8 on the southwest side of the Signal Hill fault. The test was carried well into the Brown zone, and produced 2,500 barrels of oil per day. Exploration was continued to the base of the Deep zone, or to a depth of about 7,500 feet, with the result that by 1929 more than 300 wells had been drilled to obtain a prolific production from this zone.

Exploration for still deeper production was started in 1938, when the DeSoto Oil Company drilled its No. 1 and obtained oil throughout the interval between 9,760 and 10,157 feet. The sands were named the DeSoto zone. The top of the zone corresponds approximately to the top of the Mohnian stage of the Miocene. Production from an interval several hundred feet stratigraphically below the zone was discovered in 1947 by the Shell Oil Company between 10,056 and 10,317 feet in its No. "Dolley" 2. This lower interval is considered to be part of the DeSoto zone, but is called the Dolley interval. The top corresponds approximately to the top of the lower Mohnian stage of the Miocene. Schist-bearing conglomerate, similar to that which yields oil in the El Segundo and Playa Del Rey fields farther northwest in the Los Angeles basin, was encountered less than 140 feet below the Dolley interval, but has not been productive in this or other wells that have reached it.

Accumulation throughout most of the field is anticlinal, but oil along the southwest flank is trapped in beds that have been flexed against the Signal Hill fault. This dislocation trends northwest, and is an element of the Newport-Inglewood rift. Subsurface contours suggest that the Brown zone on the northeast side of the fault has been offset southeastward approximately 3,000 feet and raised nearly 700 feet with respect to the position of the zone on the southwest side. The fault is nearly vertical down to the top of the Brown zone, but heads northeastward below that horizon and is a thrust (see structure section). Subsurface evidence indicates that displacement increases with depth and that the fault therefore has been active over a long period of time, possibly even when upper Miocene sediments were being deposited on the basement complex. Shell Oil Company's No. "Dolley" 2, drilled on the northeast side of the fault, reached schist at 10,509 feet, whereas Shell Oil Company's No. "Alamitos" 48-A, which bottomed on the southwest side, reached the schist at approximately 14,800 feet. The wells are 2,400 feet apart, and the difference in subsea depth of basement rocks, which is about 4,300 feet, probably exceeds the difference immediately adjacent to the fault. Nonetheless, this dislocation far exceeds that which affects the Brown zone. There are several less important faults in the field.

The Long Beach field is notable for the amount of horizontal drift in many of the wells that were drilled before directional surveying was developed in the early 1930's. The anomalous production obtained in certain wells has suggested lateral drift, and, in some instances, the capture of drilling tools in one well by fishing procedures in another left no doubt as to what had happened. Such astonishing and universal trespass was proved in this and other fields that in 1935 a State law was passed to place limitations on possible suits for damage and therewith eliminate the uncertainty that had arisen over the liabilities of trespassers.

REFERENCE

Stolz, H. P., 1943, Long Beach oil field: California Div. Mines, Bull. 118, pp. 320-323.

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* Consulting Geologist, Long Beach.

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

GEOLOGIC GUIDE NO. 1

WESTERN MOJAVE DESERT AND DEATH VALLEY REGION

1954

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO

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GEOLOGIC GUIDES

Guide No.

1. Geologic guide for the western Mojave Desert and Death Valley region, southern California
2. Geologic guide through the Ventura basin, southern California

Guide No.

3. Geologic guide for the Los Angeles basin, southern California
4. Geologic guide for the southwestern part of the Los Angeles basin, southern California

Guide No.

5. Geologic guide for the northern part of the Peninsular Range province, southern California

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San Francisco | Bulletin 170 | September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

GEOLOGIC GUIDE NO. 1

WESTERN MOJAVE DESERT AND DEATH VALLEY REGION

By LAUREN A. WRIGHT *and* BENNIE W. TROXEL

GEOLOGIC GUIDE FOR THE WESTERN MOJAVE DESERT AND DEATH VALLEY REGION, SOUTHERN CALIFORNIA

By Lauren A. Wright * and Bennie W. Troxel **

INTRODUCTION

This geologic guide has been prepared as a roadlog of a 580-mile circuit through the western part of the Mojave Desert and the Death Valley region of California. The rock units and structural features seen along this route indicate a long and eventful geologic history that still is incompletely studied and understood. The landscape of this vast region commonly is almost devoid of vegetation, and it shows a characteristic boldness that reflects a period of profound deformation which began as early as mid-Tertiary time and appears to be continuing today.

Deformation is most abundantly shown by major faults, some primarily normal and others primarily strike-slip, that border mountain ranges and commonly show total displacements of many thousands of feet. In the southern Death Valley area and in the region to the east, Tertiary thrust faulting has been recognized as preceding normal faulting. Recent deformation is most evident in the tilting and warping of late Pliocene lava flows, in the off setting of stream channels, and in the displacement of Quaternary alluvium.

Tertiary and Quaternary deformation has led to development of basins of nonmarine deposition and to accumulation, mainly in these intermountain areas, of thick and extensive formations of sedimentary and volcanic rocks that now are characteristically exposed in picturesque badlands or are concealed beneath younger alluvium and other deposits.

Also impressive to one who today travels through the dry, undrained basins along the route of this geologic guide are the features left by the Pleistocene lakes that once occupied these basins. Most abundant and easily recognized are the remnants of wave-cut terraces around the margins of several basins. Masses of saline minerals were deposited in some of these lakes during periods of desiccation. Two large bodies of saline minerals are present, one above the other, at Searles Lake, where brines pumped from them yield about one million tons of various salts of sodium, potassium, boron, lithium, and bromine each year. A wide variety of saline mineral species is represented, and a number of them are unique to this locality.

The Death Valley and Mojave Desert region also has served as a laboratory for many of the classical studies of geomorphic processes under arid conditions. Of particular interest in this connection are the well-developed granitic domes in the area between Barstow and Mojave, numerous pediments in several valleys and basins, and the alluvial fans in the Death Valley region which commonly show 1,000 to 3,000 feet of relief.

The pre-Tertiary history of this region is recorded mainly in the higher mountain ranges, especially in the west-trending San Bernardino and San Gabriel Mountains and Sierra Pelona that border the region on the south, in the northeast-trending El Paso Range east of the town of Mojave, and in a series of north-northwest-trending ranges that form part of the Basin Range province and include the Argus, Slate, Panamint, Amargosa, Resting Spring, and Nopah Ranges. The ranges commonly are separated by extensive low areas that are blanketed by Tertiary and Quaternary rocks, and hence serve as windows that permit a discontinuous view of the older rocks.

Noteworthy in the pre-Tertiary terrane are (1) extensive exposures, in the Death Valley area and the eastern part of the Mojave Desert, of metamorphic rocks of earlier pre-Cambrian (Archean) age; (2) the occurrence in the Death Valley area of a thick (12,000 or more feet maximum) section of only slightly metamorphosed sedimentary rocks of later pre-Cambrian (Algonkian) age; (3) the presence, in the northern part of the region, of a very thick (30,000′±), nearly complete section of Paleozoic sedimentary rocks; and (4) the occurrence of an impressive volume of plutonic igneous rocks that were intruded throughout the region during middle or late Mesozoic time. The broad features of most of the rock units that are exposed along the route of travel are summarized in other contributions in this volume (see especially Hewett, Contribution 1, Chapter II; Noble and Wright, Contribution 10, Chapter II; McCulloh, Contribution 2, Chapter VII; Oakeshott, et al., Contribution 1, Chapter III; Noble, Map Sheet 14; Dibblee, Map Sheet 13; Wright, Map Sheet 17; Bowen, Map Sheet 18; and Troxel, Map Sheet 15), as well as in the publications cited in the bibliographies of these contributions.

In addition to the bodies of saline minerals at Searles Lake, the region contains numerous other deposits and mine workings of current or historic interest. Among these are the world's largest borate operations at Kramer; the older and now idle borate mines in the Death Valley area and the Calico Mountains; the quarries near Victorville that supply most of the limestone used in southern Cali-

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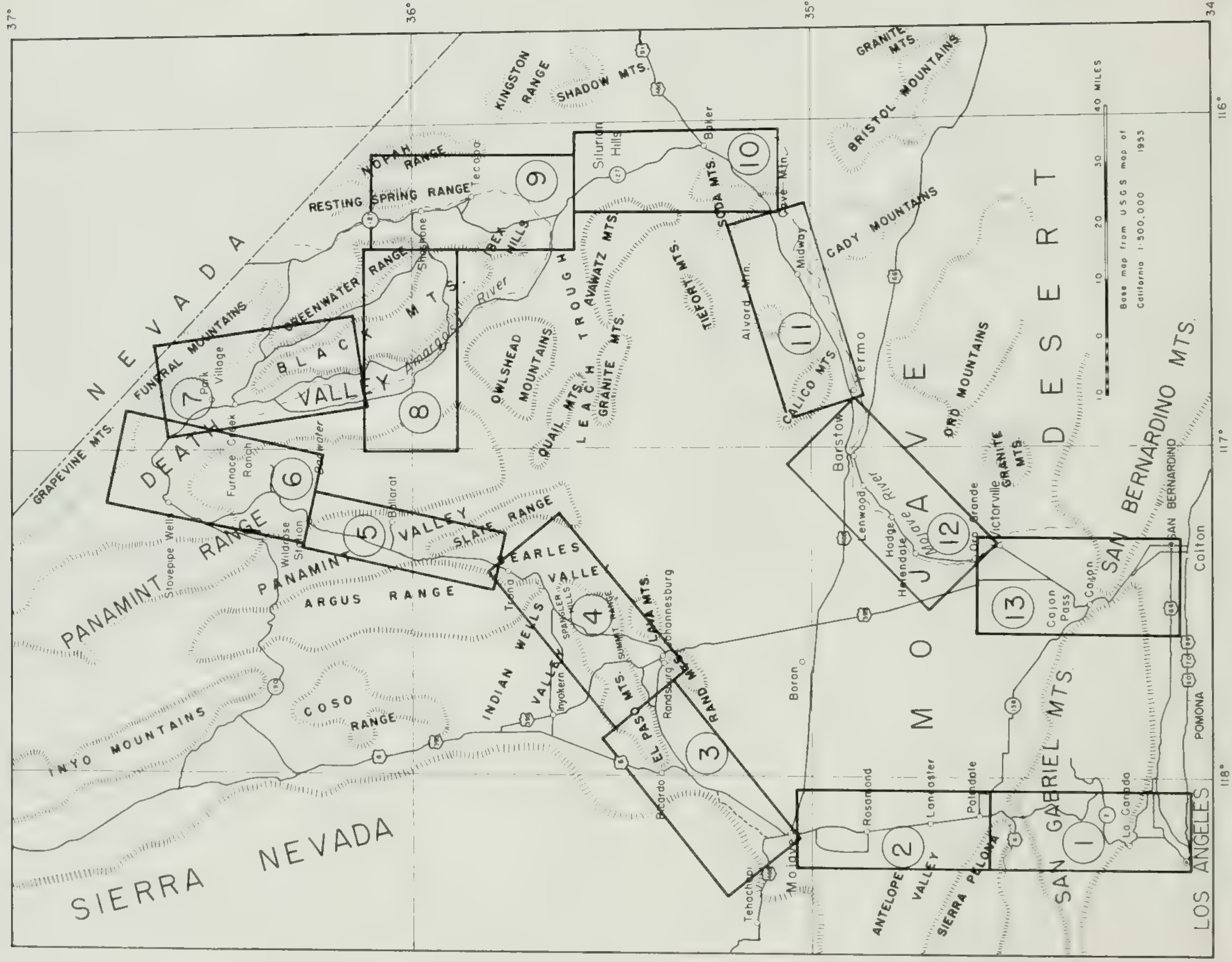


FIGURE 1. Index map of western Mojave Desert and Death Valley region showing route of road log and strip-map coverage. Geology for the strip maps is modified from the state geologic map, scale 1:250,000, now in preparation.

fornia; numerous talc mines in and near the southern part of the Death Valley area; the large, recently discovered rare-earth deposits at Mountain Pass; the rich tungsten deposits at Atolia; the historic bonanza silver camps at Calico and Red Mountain; and the gold mines in the Randsburg and Mojave-Rosamond areas.

Briefly outlined, the route of this geologic guide (fig. 1) extends generally northeastward from Los Angeles Civic Center to Death Valley by way of Palmdale, Mojave, and Trona. The return trip is through Baker, Barstow, Victorville, and San Bernardino. The description ends at San Bernardino, and for coverage of the areas south and west of this city the reader is referred to two other road logs of this series—one covering the Peninsular Range region (Geologic Guide No. 5) and the other covering the Los Angeles basin (Geologic Guide No. 3).

The round trip can be made hurriedly in 2 days, but a more enjoyable and leisurely journey of 3 or more days would permit the stops and side trips suggested below. The main route can be traveled entirely on paved roads; several of the by-passes and side trips are on dirt or gravel roads that ordinarily are in good condition. Persons who are unfamiliar with the region or who are inexperienced in desert driving should make inquiry before traveling on unimproved side roads not noted here. Good accommodations exist at numerous locations, including Mojave, Ridgecrest, Trona, Stovepipe Wells, Furnace Creek, Shoshone, Baker, and Barstow. On week ends during the winter season, reservations are highly desirable in establishments in and around Death Valley. All vehicles driven through this region should be in good repair and should have good tires. Extra water and a shovel should be carried.

Acknowledgments. In preparing this road log, the writers have drawn upon many sources of information, both published and unpublished. Descriptive material for the Pasadena-La Canada segment of the route was supplied by R. P. Sharp. The section dealing with the San Gabriel Mountains contains extracts from a road log previously prepared by R. H. Jahns and R. P. Sharp. The geological data from Soledad Pass to Garlock Station were assembled under the guidance of T. W. Dibblee, Jr., who accompanied the writers into the field and critically reviewed that part of the road log. The descriptions of the geological features seen from the Wildrose Canyon-Emigrant Pass route through the Panamint Range were supplied mostly by D. H. Sears during the course of a field trip with the writers.

The coverage of the Death Valley region from Furnace Creek Ranch to the Ibex Pass area is based largely on discussions with L. F. Noble and H. D. Curry, many of them in the field. D. H. Kupfer and L. T. Grose contributed data on the Silurian Hills and Soda Mountains, respectively. The description of the Barstow to Victorville area was prepared with the assistance of O. E. Bowen, Jr. The data for the Cajon Pass region were taken from a description by L. F. Noble (1933). Guidance of a general nature was provided by D. F. Hewett, who on many occasions has discussed geological features of the Mojave Desert region with the writers. The strip maps were extracted and modified mainly from advance sheets of the latest edition of the Geologic Map of California, now being assembled from many sources by C. J. Kundert. The interest and generous assistance of each of these contributors is gratefully acknowledged. The writers also are indebted to R. H. Jahns for a critical review of the manuscript.

ROAD LOG

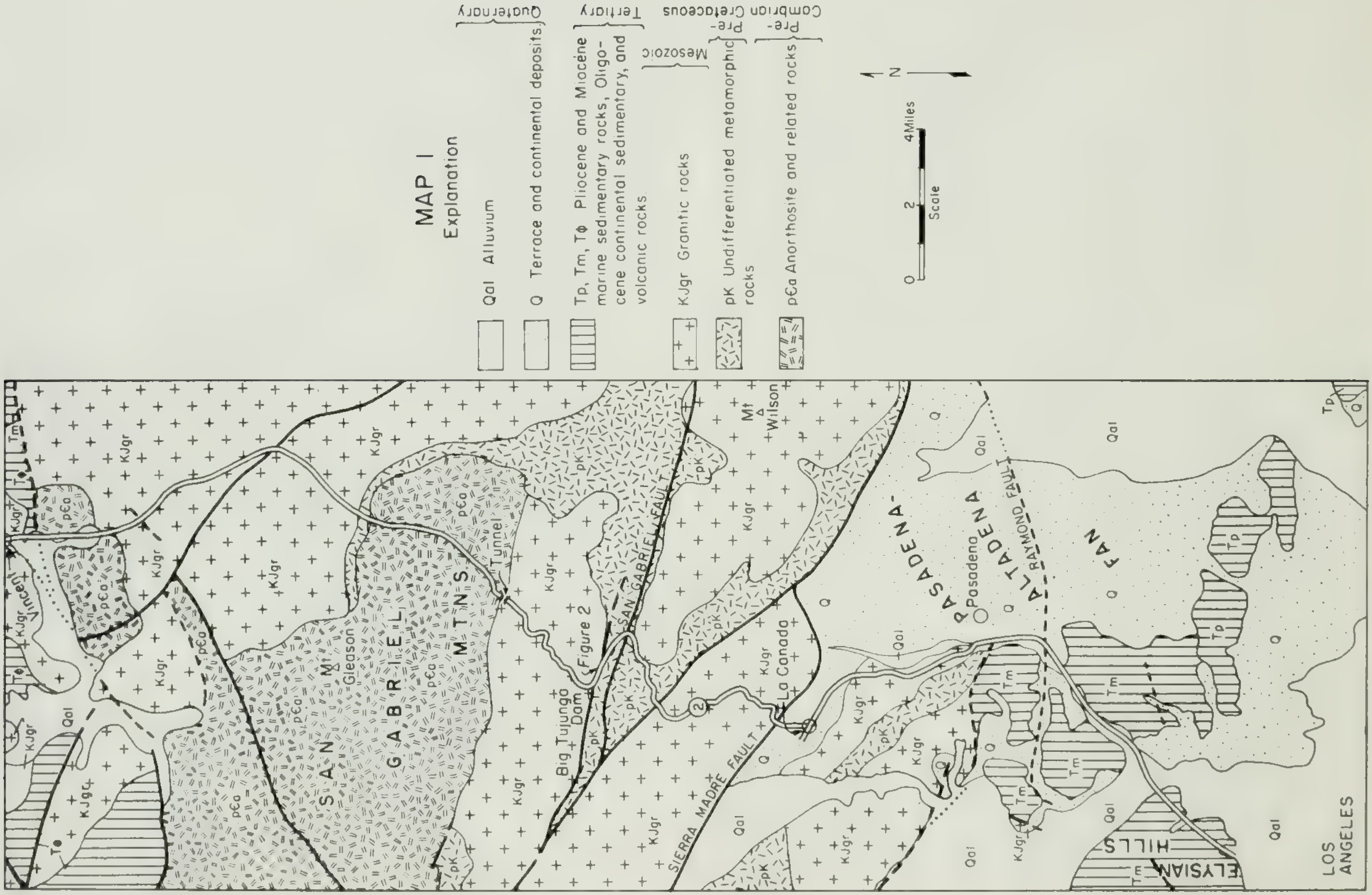
Los Angeles Civic Center to La Canada

In traveling northeastward from the Los Angeles Civic Center to Pasadena via the Arroyo Seco (Pasadenas) Freeway, one passes through low hills underlain by folded and faulted marine sandstone and shale of the upper Miocene Puente formation (Map 1). The hills are flanked and locally capped by Pleistocene terrace deposits. The Miocene rocks were deposited when the Tertiary sea extended farthest into the region now occupied by the Los Angeles metropolitan area, and are equivalent in age to some of the nonmarine basin deposits in the desert region to be seen later along the route of travel.

For about 1.8 miles northeastward from the four-level grade separation at the southern end of the Arroyo Seco Freeway to the north slope of the Elysian Hills, the route crosses the south limb of the west-trending Elysian Park anticline. The old Los Angeles City oil field, some of whose derricks still remain, lies along a secondary zone of folding and faulting in the anticline.

At 2 miles from the four-level grade separation, the freeway crosses the Los Angeles River channel near its junction with the Arroyo Seco. The steep northeast slope of the Elysian Hills has been produced largely through undercutting by the Los Angeles River. An effect of this cutting was the Elysian Park landslide of 1937, whose scar is still plainly visible a few hundred feet west (left) of the freeway. Northeast of here, the freeway enters the Arroyo Seco, and for about 2.5 miles the Puente formation is exposed along both walls of the canyon.

Turn right from the freeway at the Orange Grove Avenue turnoff, and thence left on Orange Grove Avenue. Here the avenue follows a small gully cut into a scarp that marks the trace of the Raymond fault, a west-trending reverse fault with a steep northerly dip. This fault can be traced easily for about 19 miles, and in the


MAP I
Explanation
Qal Alluvium
Q Terrace and continental deposits
Quaternary
Tp, Tm, Tφ Pliocene and Miocene marine sedimentary rocks, Oligocene continental sedimentary, and volcanic rocks
Tertiary
KJgr Granitic rocks
Mesozoic
pK Undifferentiated metamorphic rocks
Pre-Cretaceous
p€a Anorthosite and related rocks
Pre-Cambrian
N
0
2
4 Miles
Scale
Vincent
SAN GABRIEL MTNS
Mt Gleason
Tunnel
Figure 2
Big Tujunga Dam
SAN GABRIEL FAULT
Mt Wilson
La Canada
SIERRA MADRE FAULT
PASADENA-ALTADENA FAN
Pasadena
RAYMOND FAULT
ELYSIAN HILLS
LOS ANGELES
KJgr
pK
p€a
Qal
Q
Tp
Tm
Tφ

Pasadena area it is expressed by a scarp 75 to 100 feet high in Quaternary alluvial gravel of the Pasadena-Altadena fan. Within four-tenths of a mile of the turn-off, Orange Grove Avenue emerges onto the surface of the Pasadena-Altadena fan, and extends northward up this gently sloping surface. At 1.0 mile from the turn-off, a low hill on the left is a knob of lower Miocene conglomerate that projects through the fan to form an outlier of the hills west of the Arroyo Seco. About half a mile west of Orange Grove Avenue, the Arroyo Seco is incised about 150 feet below the surface of the fan.

Old channels on the fan indicate that the drainage of the Arroyo Seco once flowed farther east into the Rio Hondo and thence into the San Gabriel River. The incision of its present course into the Pasadena-Altadena fan is an effect of the diversion of this drainage into the Los Angeles River.

Turn left one block north of Colorado Boulevard, and thence eastward on Holly Street to cross the Arroyo Seco by way of the Holly Street bridge. Here the channel is narrow, as it has been superimposed upon a bedrock spur (largely diorite) that projects eastward from the San Rafael Hills. These hills are essentially a fault block that is bounded on the south by the Eagle Rock fault, a reverse fault that dips steeply northward. As this block appears to have been tilted eastward, its eastern part probably is buried beneath the Pasadena-Altadena fan. The hills are underlain mostly by the Wilson diorite (Miller, 1934) of late Mesozoic (?) age, but also contain a large septum of the San Gabriel formation, a metasedimentary series that is older than the diorite and may be pre-Cambrian in age.

After crossing the Holly Street bridge, bear right and travel northward along Linda Vista Avenue. Here the Arroyo Seco widens to provide the site of the famed Rose Bowl. For several miles the avenue lies on the surface of a terrace about 75 feet above the arroyo floor.

From 1.7 to 2.2 miles beyond the bridge, roadcut exposures show the Wilson diorite, which here is transected by many dikes of aplite, pegmatite, and granite.

At Devil's Gate Dam, the Arroyo Seco is confined to another narrow gorge because of superimposition of the stream channel upon a formerly buried spur of crystalline rocks that extends eastward from the San Rafael Hills. The dam is used primarily for flood control, but also contributes to water conservation because it promotes infiltration in the ponding basin behind it.

From the vicinity of the dam, one looks northward to the steep south face of the San Gabriel Mountains. This face is a fault scarp whose base marks the trace of the Sierra Madre fault zone, a complex of many parallel and diverging breaks that in general are reverse faults with steep northerly dips. North of Pasadena, the scarp is nearly 5,000 feet high. Movement on the fault zone has been recurrent, and began at least as early as Pliocene time. The most recent movement is shown by small scarplets in the fans.

The cluster of large buildings at the foot of the mountains directly north of Devil's Gate is the Jet Propulsion Laboratory, operated under contract by the California Institute of Technology for the U. S. Army Ordnance Corps. The flat-topped hill behind the laboratory is locally known as Gould Mesa, and is an upfaulted mass composted mostly of fan gravels that locally have been tilted northward toward the mountains. Northwest of the dam, the route follows La Canada-Verdugo Road, which lies to the west of two well-defined terraces. Turn west (left) on Foothill Boulevard and thence north on Haskill Street, which leads up the fan to the start of the Angeles Crest Highway. Note the steepness of this fan near the mountain front, as compared with the gentle slope of the Pasadena-Altadena fan along Orange Grove Avenue, at a much greater distance from the front.

La Canada to Soledad Pass

The right-angle right turn at the head of Haskill Street is in the Sierra Madre fault zone. The part of the San Gabriel Mountains traversed by the Angeles Crest and Angeles Forest Highways between this point and Soledad Pass is essentially an uplifted block between the Sierra Madre fault zone and the San Andreas and Soledad fault zones, and consists almost entirely of pre-Tertiary crystalline rocks that locally are overlain by Quaternary alluvial gravel. The pre-Tertiary rocks have been intimately fractured, and their structure is very complex in detail.

In general, the southern part of the traverse shows two principal types of rocks: (1) those of the San Gabriel formation of pre-Cambrian (?) age, a complex composed chiefly of metasedimentary rocks and metadiorite intruded lit par lit by granitic rocks, and (2) granitic rocks of Mesozoic age that intrude the San Gabriel formation. The northern part of the traverse is largely through Mesozoic granodiorite and a pre-Cambrian anorthosite complex that also contains related rocks ranging in composition from gabbro to diorite (Miller, 1934). The anorthosite proper is readily distinguished by its chalky whiteness.

From the first turnout to the right and beyond the bridge, one looks southward to the north side of the San Rafael Hills and thence southwestward beyond the Montrose gap to the Verdugo Hills. The disastrous New Year's Day flood of 1933 passed through this gap. The north face of the San Rafael Hills is a fault scarp that is overlapped by the fans sloping from the north. The Wilson diorite is exposed in the roadcuts near the turnout.

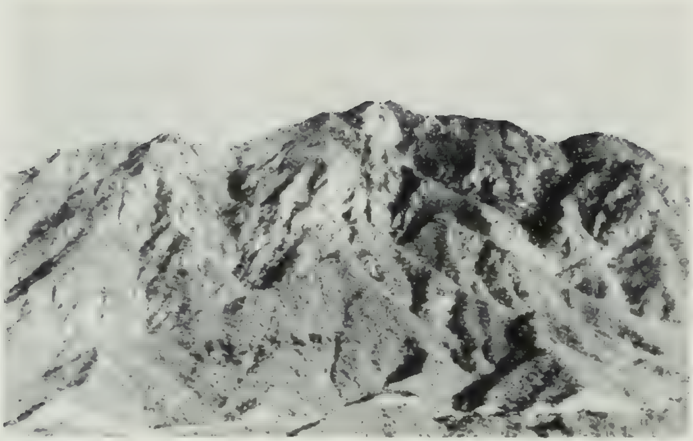


Figure 2. View north toward south slope of Josephine Mountain in San Gabriel Mountains. Abundant vegetation above and parallel to road marks trace of San Gabriel fault. Lowe granodiorite above fault; San Gabriel formation below fault. *Photo by R. H. Jahns.*

At the turnout under the power-line crossing are the first of several exposures that show alluvial gravel lying on bedrock. These particular gravels may once have been part of a fan surface that since was largely destroyed by erosion and faulting.

For a distance about 7.5 miles from the vicinity of the guard station the route lies mainly within the San Gabriel formation. At George's Gap, about 5.5 miles beyond the guard station, one looks northward into Clear Creek Canyon of the Big Tujunga drainage area. On the north side of the canyon (fig. 2) can be seen the contact zone between the light-colored Lowe granodiorite on the upper two-thirds of the slope and the brownish-weathering San Gabriel formation on the lower, less steep part of the slope. This contact marks the trace of one of the principal breaks in the San Gabriel fault zone, and is emphasized by the line of abundant vegetation that is fed by water seepage along the fault. This fault zone is one of the major structural features of southern California and is believed to have a horizontal displacement measurable in miles (Crowell, 1952). Clear Creek Canyon and Red Box divide on the skyline to the east have developed by the relatively rapid erosion of crushed rock within the zone.

At the bottom of the canyon turn west (left) from Angeles Crest Highway onto the Angeles Forest Highway along the north side of Clear Creek Canyon. About 2.5 miles from the road junction, a small turnoff to the left affords a view of the steep-walled Big Tujunga Canyon and of Dam No. 1. The Lowe granodiorite is exposed in the nearby roadcuts and at the base of the slope on the opposite (west) side of the canyon. Higher on the slope is the darker-colored Wilson diorite. On the skyline to the north is the timbered ridge of Mount Gleason, whose upper dark-colored slopes consist of the dioritic facies of the anorthosite complex. Some of the nearer light-colored slopes are underlain by the anorthosite itself.

At a point 3.4 miles beyond the turnout that overlooks the dam, a gravel-capped ridge crest is exposed. The gravel appears to have once filled a gully, and to have proved more resistant to erosion than the rocks on either side. The roadcuts in this area contain excellent exposures of a migmatitic phase of the San Gabriel formation. About 0.7 mile beyond, at the far end of the Big Tujunga Canyon bridge, the Wilson diorite is exposed.

Within 1 mile of the tunnel that lies a short distance beyond the bridge, the road enters the anorthosite complex. Roadcuts about 0.7 mile from the tunnel show diorite that is a border phase of the complex and contains consistently oriented inclusions. At points farther along the road note the dark-colored masses in anorthosite. These have been interpreted variously as dikes, inclusions, or segregations. Note also the blotchy noritic rocks that contain gigantic crystals of hypersthene. Hills to the east (right) of the road, about 3 miles from the tunnel, contain brushed out lines, made to facilitate magnetometer surveys for ilmenite concentrations in the anorthosite complex.

At the 4,900-foot summit between the Mill Creek and Aliso Canyon drainages, and for several miles on both sides of the summit, the route passes over a large body of Lowe granodiorite that is cut by numerous basic dikes. In the lower part of Kentucky Spring Canyon and about 12 miles from the tunnel, rocks of the anorthosite complex again appear in the roadcuts.

From this area, one views the upper and most easterly part of the Santa Clara River drainage. The rounded ridge that forms the highest part of the northwestern skyline is the Sierra Pelona (Map 2), which is underlain mostly by the Pelona schist, a formation that generally is believed to be pre-Cambrian in age. Diorite and gneiss of undetermined age form a belt on the lower south slope of this range. Irregularly distributed in the still lower areas are andesitic and basaltic volcanic rocks of the Vasquez formation (Oligocene). The foothills on the north flank of the San Gabriel Mountains, to the viewer's left, are underlain by rocks of the anorthosite complex.

Soledad Pass to Mojave

The traveler who proceeds eastward and northeastward through Soledad Pass will note the contrast between the nearly level surface of the Mojave Desert before him and the rugged topography of the

San Gabriel Mountains through which he has just passed. In this area the San Andreas fault zone trends west-northwestward through the foothills of the Sierra Pelona to the west and the San Gabriel Mountains to the east, and marks the approximate boundary between the Mojave Desert region and the Transverse Range province. This fault zone, which is one of the State's major structural features, has been traced from Point Arena in northern California for 600 miles southeastward into the Imperial Valley area (Hill and Dibblee, 1953). Movement along it has caused several major earthquakes, including the great San Francisco earthquake of 1906.

The channel that slopes northward from Soledad Pass once received the northward drainage from Kentucky Springs Canyon, which is followed by the lower part of the Angeles Forest Highway. This drainage, however, has been captured by headward erosion of the Santa Clara River, an intermittent stream that flows westward through the Ventura basin to the sea near Ventura.

In the Soledad Pass-Palmdale-Pearland area (Wallace, 1949; Noble, 1953; Dibblee, personal communication, 1954) the San Andreas fault zone is as much as 3 miles wide and involves slices of the Pelona schist (pre-Cambrian ?), granitic rocks, and several types of younger sedimentary rocks. Within the zone most of the Recent movement has occurred along a single break ordinarily designated as the San Andreas fault. In the area along the route of travel this main break is flanked on both sides by belts of highly deformed Tertiary nonmarine strata—the Punchbowl formation on the south and the Anaverde formation on the north. These formations are each about 1,500 feet thick and are conglomeratic and arkosic sandstone; but they differ from each other in that the Punchbowl formation contains clasts of heterogeneous rock types, all apparently derived from rocks south of the fault, whereas the clasts in the Anaverde formation are of granitic composition and apparently were derived from rocks north of the fault. Although Punchbowl strata have yielded Miocene vertebrate remains and Anaverde strata have yielded Pliocene leaves, the two formations may have been deposited at different places in essentially the same upper Miocene-lower Pliocene time interval and have been brought into contact by horizontal movement along the San Andreas fault.

The Tertiary and pre-Tertiary rocks are overlain by several hundred feet of Pleistocene terrace deposits (the older Harold formation and the younger Nadeau gravel). These generally are flat-lying, but they have been involved in movements along the San Andreas fault zone.

Northwest of the road at Soledad Pass are exposures of andesite flow breccias of the Vasquez formation (Oligocene-lower Miocene). The hill southeast of the road is underlain by Mesozoic granitic rocks. The west roadcut at the junction of U. S. Highway 6 with Pearblossom Highway exposes the north-dipping coarse, pink, basal conglomerate of the upper Miocene Punchbowl formation (Noble, 1953), which here is composed of volcanic debris derived from the unconformably underlying Vasquez formation.

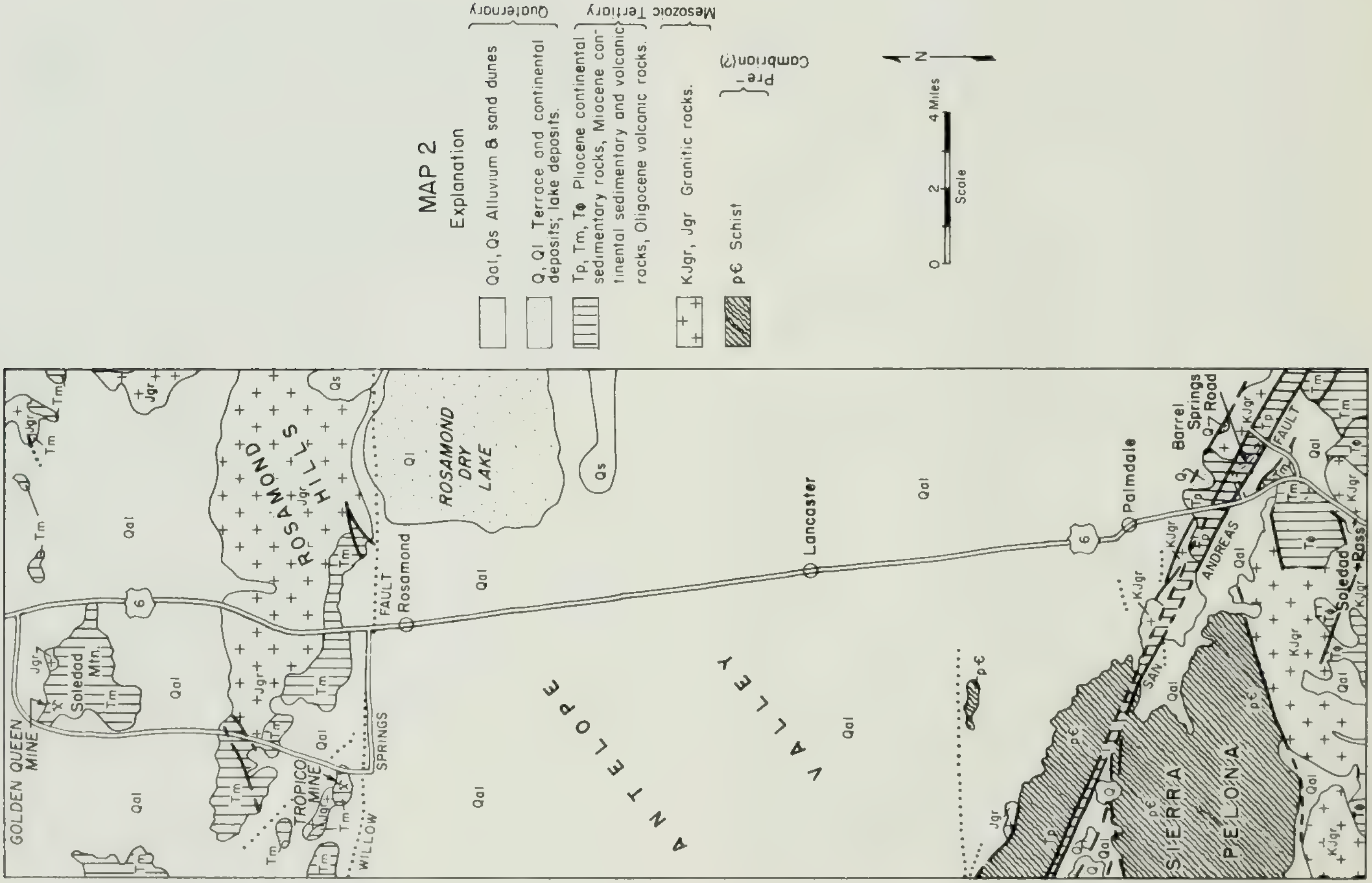
The general features of the San Andreas fault zone, which one enters in the vicinity of the road junction, can be seen best by traveling 1.5 miles northeastward on Pearblossom Highway to Barrel Springs Road, and thence west-northwestward to rejoin U. S. Highway 6 near Una Lake. Exposed in the roadcuts along this part of Pearblossom Highway are nearly flat-lying Pleistocene conglomerates with clasts of schist and granitic rocks, as well as steeply dipping arkosic sandstone of the Punchbowl formation. The angular unconformity that separates these two formations is well shown immediately west of the railroad crossing.

Barrel Springs Road lies on the principal break of the San Andreas fault. From the west side of the hill just northwest of the road junction, one can look east-southeastward along the north flank of the San Gabriel Mountains and see two prominent notches in the far distance. The more southerly notch marks the trace of the San Jacinto fault. The trace of the San Andreas fault passes through the other notch and follows a straight course northwest through the San Gabriel foothills and through the small valley a few hundred feet south of the observer to the north side of Palmdale Reservoir, where the prominent south-facing fault scarp has been used as a natural dam. Beyond the reservoir, the fault zone is marked by the elongate Anaverde, Leonis, and Elizabeth Lake Valleys.

The 60-mile segment of the San Andreas fault that is visible from this point is a very straight, trench-like feature flanked on one or both sides by long, low fault scarps and in places containing undrained depressions and sag ponds. No high scarps, characteristic of many faults with great vertical displacement, are present along this zone of rupture.

The hill upon which the observer stands is on the north side of the San Andreas fault, and lies within the belt of Tertiary rocks noted above.

The hill is flanked by Pleistocene gravel (Harold formation) which contains abundant clasts of Pelona schist and extends eastward for a distance of about 10 miles north of the fault. The Pleistocene gravel (Harold formation) across the fault to the south contains gigantic clasts and is devoid of Pelona schist. The schist debris on the north side of the fault could not have been derived from nearby hills as the nearest exposures of Pelona schist lie south of the fault and about 3 miles to the west. Such differences in composition suggest that Pleistocene deposits, juxtaposed on opposite sides of the



MAP 2

Explanation
Qal, Qs Alluvium & sand dunes
Q, Ql Terrace and continental deposits; lake deposits.
Quaternary
Tp, Tm, To Pliocene continental sedimentary rocks, Miocene continental sedimentary and volcanic rocks, Oligocene volcanic rocks.
Tertiary
KJgr, Jgr Granitic rocks.
Mesozoic
p€ Schist
Pre-Cambrian(?)
N
0
2
4 Miles
Scale
GOLDEN QUEEN MINE
Soledad Mtn.
TROPICO MINE
WILLOW SPRINGS FAULT
ROSAMOND HILLS
Rosamond
ROSAMOND DRY LAKE
6
Lancaster
ANTELOPE VALLEY
Palmdale
Barrel Springs Road
SAN ANDREAS FAULT
Soledad Pass
SIERRA PELONA
Qal
Qs
Ql
Q
Tm
Tp
To
Jgr
KJgr
p€

fault, have been brought together by horizontal movement. Although the movement cannot be measured accurately, it may have totalled as much as 5 miles in late Pleistocene and Recent time (Noble, 1953).

A fault subsidiary to the main break of the San Andreas is well exposed in a cut on the south side of Pearblossom Highway, about 300 feet northeast of its junction with Barrel Springs Road. Here the Pleistocene schist-bearing conglomerate on the west is in fault contact with nearby vertical sandstone strata of the Anaverde formation on the east.

The route of Barrel Springs Road toward Palmdale is flanked by prominent fault scarps and sag ponds that are characteristic of the main San Andreas rift. An angular unconformity between the steeply dipping Anaverde formation and a terrace capping of nearly horizontal Pleistocene gravels can be seen near the top of the most prominent ridge north of the road. These same two units, in fault contact, are exposed in a roadcut on U. S. Highway 6 and a few hundred feet northwest of Una Lake, which is the largest of the sag ponds noted above.

For a distance of 19 miles from Palmdale through Lancaster to Rosamond, U. S. Highway 6 traverses the nearly level, alluvium-floored Antelope Valley. The depth of the pre-Tertiary basement rocks has not been determined in this valley. That it probably is great was shown in 1951 by an exploratory well drilled for oil in Rosamond Dry Lake, which penetrated coarse sandy alluvial sediments, and bottomed in them at a depth of 5,500 feet (Dibblee, T. W., Jr., personal communication, 1954).

The broad features of the west-trending Rosamond Hills perhaps can be best observed from near the point at which U. S. Highway 6 crosses the Los Angeles County-Kern County line. The hills consist of Mesozoic quartz monzonite that is flanked on the south by south-dipping strata of the Rosamond series (Miocene ?) (Simpson, 1934).

In general, the Rosamond section is about 2,500 feet in maximum thickness, and consists of a lower sequence of light-colored rhyolitic tuff and an upper sequence of conglomerate rich in rhyolitic volcanic debris. The rhyolitic tuff is cut by many intrusive plugs of reddish rhyolite, and contains some rhyolite breccias that originated from some of these plugs. Thus the rhyolite and the tuff are at least in part contemporaneous.

That some faulting has occurred along the south margin of the Rosamond Hills is indicated by prominent scarps in the alluvium at Willow Springs, south-southwest of the hills, and is suggested by the straightness of the south face and by the presence of a much greater thickness of alluvium south of the hills than north of them.

The principal geological features of the Rosamond-Mojave area are best seen from an alternate route that lies west of U. S. Highway 6. From Rosamond travel west on Willow Springs Road for 3½ miles, and thence north on Tropico Mojave Road. The Tropico mine, on the hill northwest of the road junction, was one of the few gold mines still active in southern California in 1954.

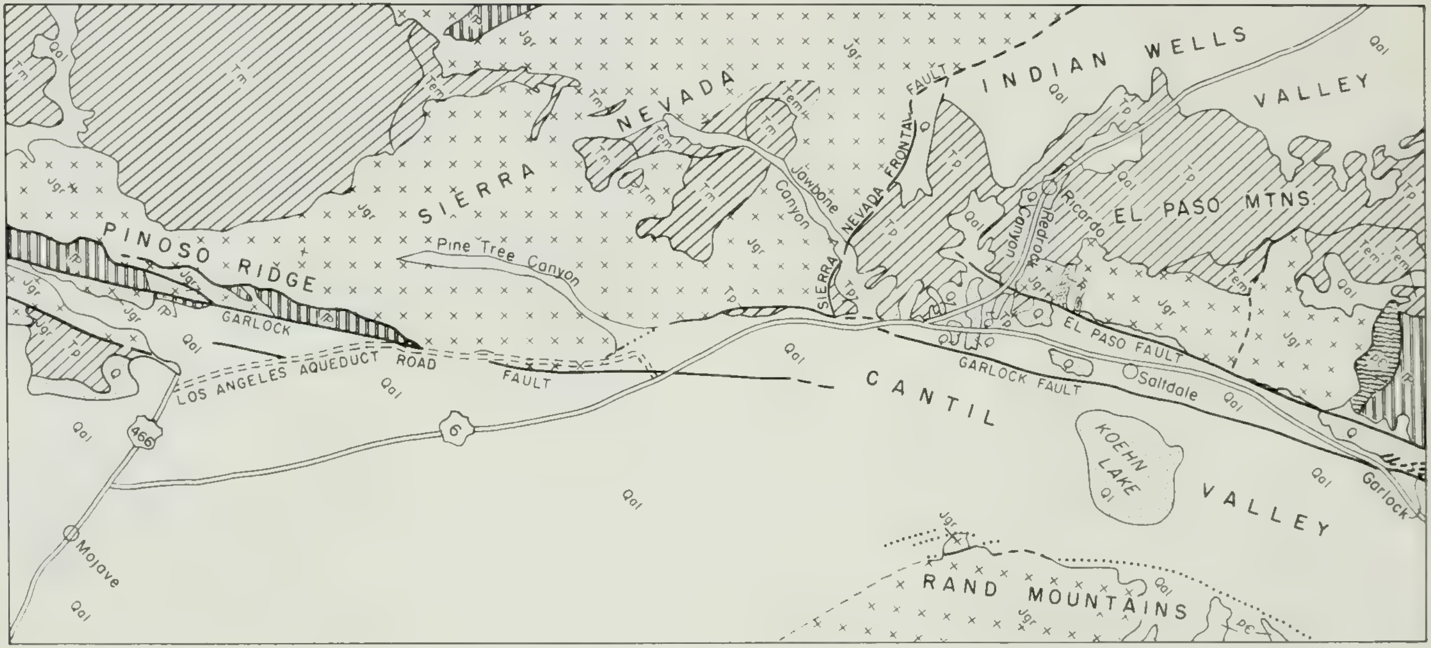
From the Tropico mine area northward to the crest of the Rosamond Hills, Tropico Mojave Road traverses south-dipping tuffaceous (light-colored) and conglomeratic (reddish) units of the Rosamond series. Near the crest the depositional contact between rhyolitic tuff and the underlying quartz monzonite is well exposed. The shallow prospect workings in this area have been developed along occurrences of the uranium-bearing mineral autunite (Walker, 1954), along fractures in the tuff. This part of the Rosamond series contains local basalt flows.

Soledad Mountain, which can be viewed to the north from the crest of the Rosamond Hills, consists of a group of rhyolite plugs that are intrusive into both rhyolite tuff and breccias of the Rosamond series, as well as the Mesozoic granitic rocks. The granitic rocks are exposed out of view low on the northeast flank of the mountain. The tuff, which contains a single basalt flow, underlies the lower part of the south flank of the mountains. The intrusive rhyolite of Soledad Mountain marks the center of an area of volcanism that has a radius of about 10 miles. Within this area are numerous smaller rhyolite plugs, including those of the Rosamond Hills, Tropico and Willow Springs Hills, and Middle Buttes, that project as rugged knobs above the smooth desert floor. On this floor is an alluvial veneer, ordinarily a few tens of feet or less in thickness, that lies upon Mesozoic granitic rocks.

Travel northward and eastward along the west flank of Soledad Mountain to an outcrop of rhyolite, at the northwest tip of the mountain. This is one of many satellitic plugs around Soledad Mountain. Looking to the west, north, and northeast, one can observe a 25-mile segment of the trace of the Garlock fault zone. This trace passes through a rift-like depression between Double Mountain, the three-pointed peak on the western horizon, and an even-crested lower ridge to the southeast. Farther northeastward the fault is marked by a depression that extends across U. S. Highway 466 near Tehachapi Pass, and thence along the base of the steep southeast front of the Sierra Nevada, north of the town of Mojave, to the base of El Paso Mountain still farther to the northeast.

The Garlock fault zone lies within pre-Tertiary crystalline rocks throughout the Tehachapi Mountains to the west.

Double Mountain consists of a quartz diorite facies of the Mesozoic Sierra Nevada batholith. The lower ridge southeast of the Garlock fault zone is underlain by granitic rocks that contain pendants of Paleozoic (?) metamorphic rocks, and in places both rock types are cut by many dikes of Miocene (?) rhyolite. In the low foothills



MAP 3

Explanation

▭ Qal Alluvium } Quaternary

▭ Q, Ql Terrace, continental and lake deposits } Quaternary

▥ Tp, Tm, Tem Pliocene and Miocene continental sedimentary and volcanic rocks, Eocene to lower Miocene continental sedimentary rocks. } Tertiary

+ Jgr Granitic rocks } Mesozoic

▒ ŦR(?) Metasedimentary rocks } Mesozoic

▧ ℙ Marine metasedimentary and metavolcanic rocks } Paleozoic

▨ pЄ Undifferentiated metamorphic rocks } Pre-Cambrian (?)

0 2 4 Miles

Scale

N

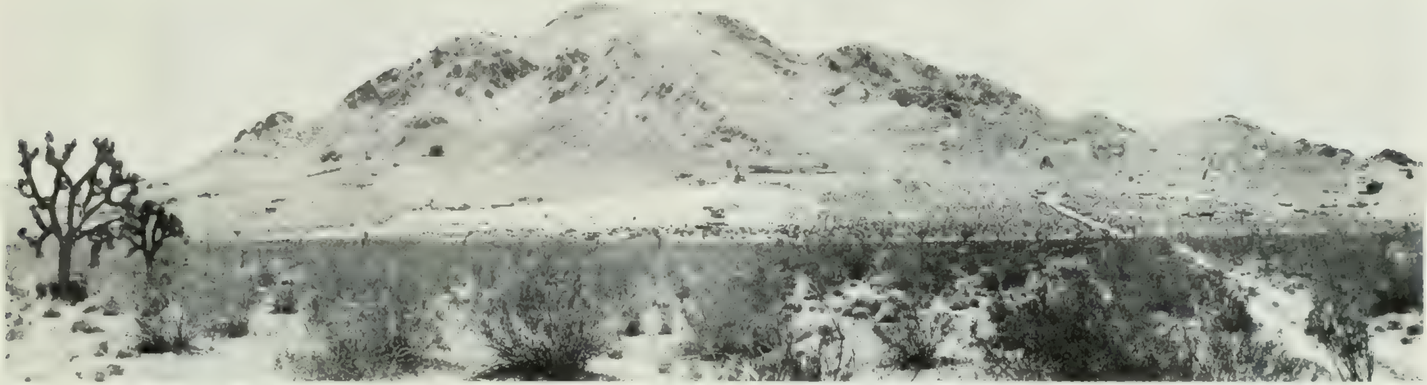


Figure 3. View of north face of Soledad Mountain, which consists of a group of Tertiary rhyolite plugs. Mine dump and mill tailings of Golden Queen mine in center.

of this ridge in the area northwest of Mojave, the granitic rocks are overlain by about 2,500 feet of Pliocene (?) terrestrial and lacustrine sediments, which in turn are overlain unconformably by about 700 feet of Pleistocene sands and coarse gravels. The Pliocene strata dip southeastward, and locally have been folded. The overlying Pleistocene beds are involved in some of this folding.

Follow the road around the north flank of Soledad Mountain (fig. 3). The rocky spurs on the northwest and north flanks of the mountain are dikes of the same rhyolite that forms the main part of the mountain. The granitic rocks, into which the rhyolite is intrusive, are exposed in a saddle between the main mountain and a small hill of rhyolite on its northeast margin.

The numerous workings in Soledad Mountain have been developed in gold deposits in brecciated and sheared zones in the rhyolite. The tailings pile and the largest mine dumps are those of the Golden Queen mine, which was opened following discovery of a major deposit in 1933. Gold mining in this district, however, has been active since 1894, and the total output is valued at about 12 million dollars.

Mojave to Garlock Station

Travel eastward to U. S. Highway 6, and thence northward through Mojave (Map 3). An improved dirt road that parallels the Los Angeles aqueduct passes near some noteworthy features of the Garlock fault, and permits a view of the western Mojave Desert and Cantil Valley that is better than that obtained from U. S. Highway 6. This road, which this geologic guide follows for about 14 miles, turns off U. S. Highway 466 about 4 miles northwest of Mojave. It can be by-passed, if the traveler prefers to remain on U. S. Highway 6 in traveling northeastward from Mojave.

Northwest of the aqueduct road, and 1 to 2 miles beyond its junction with U. S. Highway 466, is a southeast facing scarp, about 200 feet high, in the Quaternary fanglomerate. This scarp, formed by vertical movement on a subsidiary fault that is parallel to and a mile south of the Garlock fault, is one of the many breaks that indicate recent movement along the Garlock fault zone. From this locality a southeastward panoramic view of the western Mojave Desert reveals two types of prominences. The small rugged hills are rhyolite plugs; the broad smooth domes are underlain by granitic rocks. The granitic rock characteristically erodes to slopes of low relief in the arid desert climate, and the domes are generally believed to have formed in the final stage of the erosion of desert mountains (Davis, 1933). At least some of the granitic domes in the southern California desert, however, appear to have been developed by warping (Sharp, Contribution 8, Chapter V). The Mojave block has reached a stage of late maturity to old age, in the classic terminology of the erosion cycle. This is in marked contrast to the elevated Sierra Nevada block, which is in the stage of early maturity.

An excellent northward view of the precipitous front of Pinoso Ridge, the most southerly part of the Sierra Nevada, can be obtained

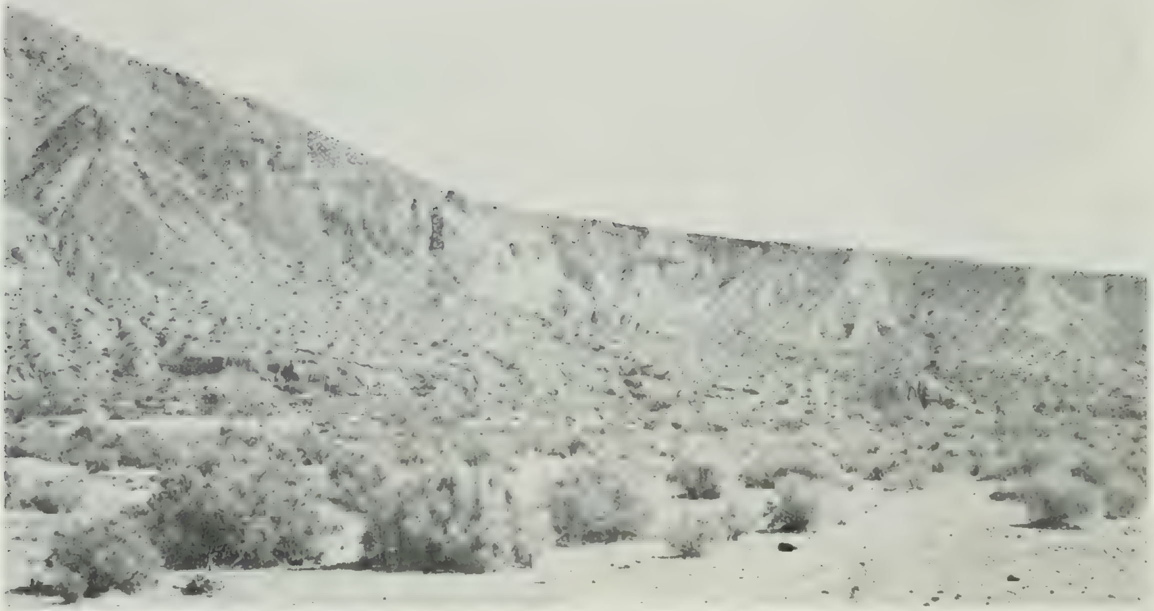


FIGURE 4. Exposure of El Paso fault, a branch of the Garlock fault zone, east of Redrock station. Light-colored Tertiary and Quaternary rocks on right are in fault contact with darker-colored Mesozoic granitic rocks on left. Sedimentary rocks of Pliocene Ricardo formation are unconformably overlain by Pleistocene terrace deposits.

from the aqueduct road beyond the turnoff from Highway 466. This mountain ridge is composed of Jurassic (?) granitic rocks of the Sierra Nevada batholith. The trace of the actual Garlock fault lies at the base of the ridge. The lower slopes of the ridge are cut by numerous zones of gouge that trend parallel to the Garlock fault and dip gently to steeply northwestward away from it. These are thrust faults along which the mountain block has been elevated; they form a part of the general Garlock fault zone which here is as much as a mile wide. Within the zone are slivers of highly sheared biotite schist and brecciated limestone, which appear as dark, blue-gray streaks in lighter-gray granitic rock. Under favorable conditions of lighting some white patches can be seen in several of the saddles on the crest of Pinoso Ridge. These are exposures of tuff and tuff-breccia that rest upon the granitic rocks and form the base of a 3,000-foot series of Miocene tuff, lavas, and sedimentary rocks that dip northwestward into a large syncline.

About 3 miles from the aqueduct road turnoff, the zone of thrust faults passes through the badlands of the lower slopes of Pinoso Ridge. The zone here narrows to a width of about half a mile, and the granitic rock has been severely sheared. It is transected by numerous parallel, steeply dipping layers of gouge. This zone converges with the Garlock fault where the aqueduct road meets the foot of the mountains about 5 miles from the turnoff. For a distance of an additional 4 miles from this point, the road lies near the actual trace of the Garlock fault.

Several small washes that cross this part of the fault from the northwest have been offset to the northeast, indicating that the land southeast of the fault has moved northeastward in Recent time.

As the road approaches the mouth of Pine Tree Canyon, it passes through a graben in which Quaternary alluvium has been dropped down between two branches of the Garlock fault. The southeast and main branch maintains a straight northeastward course southeast of the road, and forms a low, northwest-facing scarp of Mesozoic granitic rock. The northwest branch, which borders the graben on the northwest, lies at the base of the mountain front and follows it northeastward across the mouth of Pine Tree Canyon.

Turn eastward (right) on the Pine Tree Canyon road and return to U. S. Highway 6. The low, northwest-facing scarp of the main Garlock break is again crossed near the road junction. Northeastward from this point the fault can be traced in the alluvium for 2 miles, and thence disappears. For a distance of about 8 miles from its junction with the Pine Tree Canyon road, U. S. Highway 6 follows a northeastward course within the Garlock fault zone, and at most places is within a mile of the north branch that bounds the Sierra Nevada mountain front. Four miles from the Pine Tree Canyon road junction, this fault is well exposed a few hundred yards northwest of U. S. Highway 6, where it brings Mesozoic granodiorite on the north against deformed Pleistocene gravels of the valley block.

Four and three-tenths miles from the road junction and half a mile southwest of the mouth of Jawbone Canyon, a north-trending major fault is exposed on the mountain front north of the highway. This break is the southern end of the principal branch of the great frontal fault zone that borders the eastern face of the Sierra Nevada. In the Jawbone Canyon area, it is a steeply dipping normal fault, and has brought gray granodiorite of the Sierra Nevada batholith on the west (left) into contact with brilliantly colored rocks of the Pliocene Ricardo formation and overlying Quaternary terrace deposits (Samsel, H., personal communication, 1952).

The main route of this guide follows the Cantil Valley road, which branches from U. S. Highway 6 about a mile beyond Jawbone Canyon, but a 9-mile side trip to the head of Redrock Canyon via U. S. Highway 6 leads through an unusually scenic area in which the Ricardo formation is well exposed. From the road junction to Redrock Station at the mouth of Redrock Canyon, a distance of about 2½ miles, U. S. Highway 6 traverses hills underlain by folded sandstone strata of the Ricardo formation, and capped by Pleistocene terrace gravels. These hills lie in a wedge within the Garlock fault zone, and their dissection is attributable to erosion following late Pleistocene to Recent uplift of the wedge.

At the mouth of the canyon and just east of Redrock Station, pre-Tertiary crystalline rocks on the north (left) are in fault contact with folded sandstone of the Ricardo formation and less deformed but considerably dissected Pleistocene terrace gravels (fig. 4). This branch of the Garlock fault zone, named the El Paso fault by Dibblee (1952), here dips steeply northward. This fault forms the steep southeast front of the El Paso Mountains, and its trace approximately coincides with the base of the mountains for about 14 miles northward from Redrock station. This fault eventually joins the main Garlock fault near the east end of the range.

For a distance of about 1 mile north of Redrock Station, the drainage of Redrock Canyon has cut through a resistant ridge of Mesozoic granitic rocks that form the western end of the El Paso Mountains. On the northwest flank of this ridge the Ricardo formation rests with depositional contact upon the crystalline rocks, and the relatively soft beds of this formation have been eroded to form an amphitheater that long has been a favorite location in the production of western motion pictures (fig. 5).

The highway up Redrock Canyon traverses the Ricardo formation, which attains a maximum thickness of 7,000 feet between this canyon and Last Chance Canyon, about 5 miles to the northeast. This formation consists of tuff, chert, siltstone, sandstone, and conglomerate. Coarse cobble conglomerates of granitic and volcanic debris predominate from Redrock Canyon westerly to the Sierra Nevada, whereas finer-grained sediments and tuff are more abundant to the east. The formation was deposited in a broad basin. The part of the basin that lies between El Paso Mountains and the Sierra Nevada subsided most rapidly and received the greatest thickness of sediments (Dibblee, 1952). Basalt flows and tuff beds occur as resistant, cliff-forming layers (fig. 5). Two prominent flows of basalt extend across the canyon bottom near Ricardo Station. The Ricardo formation has yielded a large assemblage of lower Pliocene mammal remains, mainly from its upper part. In Last Chance Canyon the Ricardo formation rests unconformably upon the older Tertiary Goler formation (Dibblee, 1952).

A turnout, at a high point on the road and about 4 miles beyond Ricardo Station, provides a splendid view of the western portion of Indian Wells Valley, which is bounded on the northwest by the southern Sierra Nevada and on the southeast by El Paso Mountains. The Coso Range is on the distant skyline, just to the left of the line of the road.

The Sierra Nevada, which here consists largely of granitic rocks of the Sierra Nevada batholith, is bordered on the east by the frontal fault seen in the Jawbone Canyon area. Black Mountain, a high point of El Paso Mountains to the east, is capped by Pleistocene basalt that unconformably overlies tuff of the Ricardo formation. In this area, the Ricardo formation contains pumice layers that are mined for use as abrasive and light-weight aggregate.

Return to the Cantil Valley turnoff, and travel northeastward along the flank of El Paso Mountains. Cantil Valley, which can be viewed from a point 1.3 miles from the turnoff, probably is a down-dropped block between El Paso Mountains on the northwest

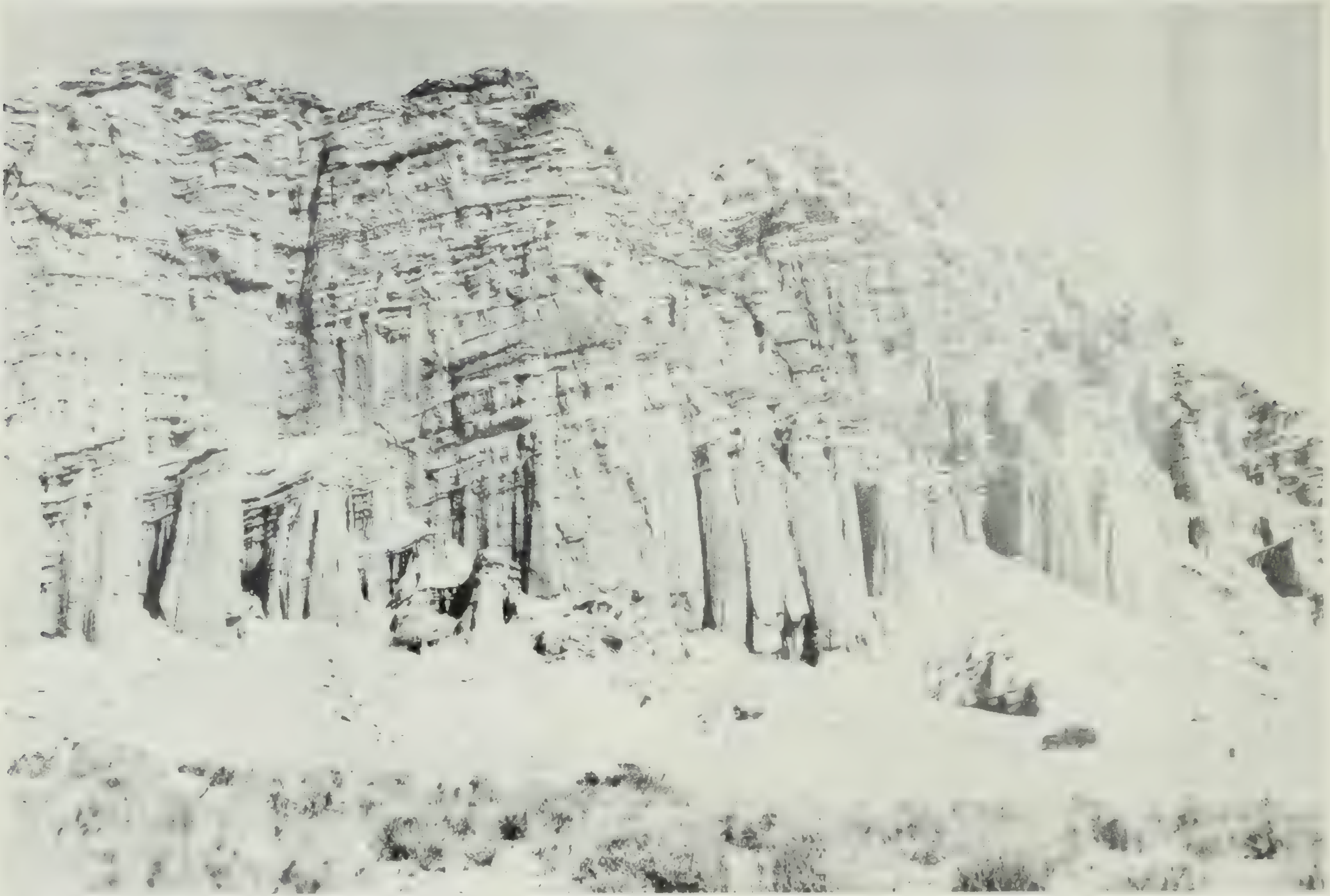


FIGURE 5. Cliff in lower Redrock Canyon composed mostly of brilliantly colored sandstone and conglomerate of Pliocene Ricardo formation.

and the Rand Mountains on the southeast. It is an undrained basin whose lowest portion contains Koehn Dry Lake. In Pleistocene time this basin was occupied by a shallow saline lake. The farm lands in the western part of the valley have been recently developed, and are irrigated with well water drawn from the higher parts of the valley.

The southeast slope of El Paso Mountains consists chiefly of pre-Tertiary igneous and metamorphic rocks. In the southern part of the range these are mainly Mesozoic plutonic rocks that are intrusive into pre-Cambrian (?) schist and a thick northeast-dipping series of Paleozoic sedimentary and metavolcanic rocks (Garlock series). These older rocks underlie most of the central part of the range.

On the northwest flank of the mountains is a section of Tertiary rocks composed of the Ricardo formation (Pliocene), which was seen in Redrock Canyon, and the Goler formation (Eocene to lower Miocene), which underlies the Ricardo formation in the Last Chance Canyon area. These formations dip northwestward, the Goler strata moderately and the Ricardo gently. The Ricardo formation locally is capped by the Black Mountain basalt, of Pleistocene age, which likewise dips northwestward but at lower angles. These relationships indicate that El Paso Range was elevated as a block on El Paso fault and was tilted northwestward in mid-Tertiary time, again in late Pliocene-early Pleistocene time, and once again in late Pleistocene time.

El Paso branch of the Garlock fault zone continues northeastward along the base of El Paso Mountains, but the break of most recent movement lies within the valley and near the north side of Koehn Dry Lake. The trace of this most recently active fault is indicated by the prominent scarp in the alluvium northeast of the lake.

The Rand Mountains are underlain by pre-Cambrian (?) schist that is exposed on their north flank, and intrusive into this metamorphic terrane are Mesozoic granitic rocks. The mountains have a relatively steep northwest front that is parallel to the Garlock fault zone and may mark the position of a bounding fault. If this fault exists, it shows no evidence of recent movement and its trace lies largely hidden beneath alluvium.

At Saltdale, brine pumped from beneath the surface of the dry lake is evaporated in ponds to yield commercial salt (NaCl). This plant has been operated since 1920, but is shut down during unusually dry years. Two miles northwest of the Saltdale turnoff, the road crosses a fossil sand bar, which was formed in the Pleistocene lake that once occupied Cantil Valley.

Mesquite Canyon, which drains into Cantil Valley at a point about 5½ miles northeast of Saltdale, approximately marks the base of the Paleozoic section (Garlock series) that dips northeast and is exposed along the front of the mountains for a distance of about 9 miles northeast of the canyon. This section is about 35,000 feet thick, and consists mostly of chert, shale, limestone, and altered volcanic rocks. It appears to be homoclinal, but possibly is involved in isoclinal folding (Dibblee, 1952). Permian fossils have been found in beds near the center of the section, and at least the upper half of the section appears to be of this age. The exact age of the lower half remains undetermined. In Mesquite Canyon, the Paleozoic rocks overlie a belt of schist that probably is pre-Cambrian in age (Dibblee, 1952).

Near the mouth of Mesquite Canyon, the road passes just south of a south-facing scarp in Quaternary rocks. It is about 2 miles long and as much as 280 feet high. Northwest-dipping Pleistocene sandstone is exposed at its southwestern end, and several springs issue from the base of the scarp.

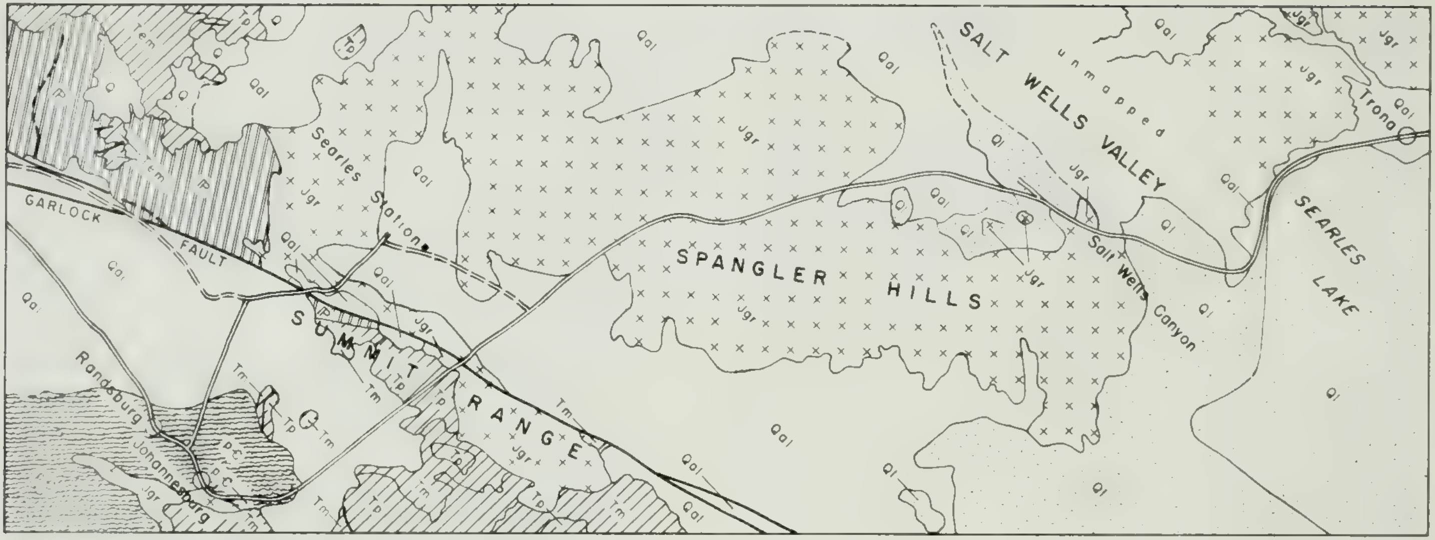
At the settlement of Garlock, which is the type locality for the Garlock fault and lies about 1 mile northeast of the turnoff to Randsburg, this scarp is joined at its northeast end by another scarp that faces the mountain front. This north-facing scarp indicates a several-hundred-foot movement northeastward of the land southeast of the fault. The drag created by this movement has produced a series of northeast-trending tension grabens that appear as shallow depressions in the alluvium northwest of the fault. These can be seen to the left of the side road that leads from Garlock to Mesquite Canyon.

Another prominent northwest-facing scarp marks the trace of the Garlock fault at the mouth of Goler Gulch, about 2 miles northeast of the settlement of Garlock (Hulin, 1925) (Map 4). The recency of the faulting is emphasized by the existance of a small undrained depression at the base of the scarp. Although the depression drains an area of several square miles, it has received a relatively small volume of detritus.

Garlock to Wildrose Canyon

From the junction of the Cantil Valley road with U. S. Highway 395, one can look southward at the gray slopes of the northern part of the Rand Mountains, which consist mainly of the Rand schist (pre-Cambrian), and at the town of Randsburg. Red Mountain, which forms the high point on the horizon to the left of Randsburg, consists of nonmarine sedimentary rocks capped by andesite, all of late Tertiary age.

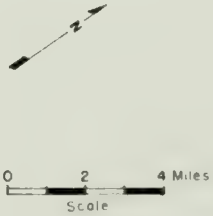
Randsburg was settled in 1895, following the discovery of gold in the area. The gold deposits of this district were subsequently worked in numerous mines; by far the largest is the Yellow Aster, whose tailings and dumps are prominent on the hillslope southwest of



MAP 4

EXPLANATION

☐	Qal	Alluvium	Quaternary
☐	Q, Ql	Terrace deposits and volcanic rocks, lake deposits	
▥	Tp, Tm, Tem	Pliocene and Miocene continental sedimentary and volcanic rocks, Eocene to lower Miocene continental sedimentary rocks	Tertiary
+	Jgr	Granitic rocks	Mesozoic
▒	IP	Marine metasedimentary and metavolcanic rocks	Paleozoic
▨	p-C	undifferentiated metamorphic rocks	pre-Cambrian (?)



Randsburg. This mine, which was worked most actively during the period 1895-1918, has yielded ore valued at $12,000,000 or more (Tucker, et al., 1949). The gold occurs within or near quartz veinlets in a body of Jurassic (?) quartz monzonite that is intrusive into the Rand schist (Hulin, 1925).

Silver deposits at Red Mountain and tungsten deposits at Atolia also are in the northern part of the Rand Mountains, and are comparable to the gold deposits in commercial importance. Both of these localities are south of Johannesburg on U. S. Highway 395, beyond the limit of Map 4. The silver deposits are Tertiary in age, and occur in siliceous veins that cut the Rand schist (Hulin, 1925; Wright, et al., 1953). They were discovered in 1919 and have been worked mainly in one mine, the Kelly. Mining was most intensive during the period 1919-29. The total output of this mine is valued at about $16,000,000.

The Atolia deposits have been in almost continuous operation since their discovery in 1904. They have yielded about 20,000,000 pounds of WO_3, and remain one of the nation's principal sources of tungsten. Scheelite, the chief ore mineral, occurs in both vein and placer deposits. The veins, some of which are world-famous for the richness of their scheelite concentrations, occur in quartz monzonite and contain a quartz-carbonate gangue.

From the main route of this geologic guide, these three mining areas are most easily visited by means of a 10-mile side trip via U. S. Highway 395. The Rand schist is well exposed in road cuts on the approach to Randsburg.

In travelling northward on U. S. Highway 395, one passes through dissected Quaternary terrace gravels and again crosses the Garlock fault zone about a mile from the junction of this highway with the Cantil Valley road. From the vicinity of the turnoff at the crest of the ridge, the fault zone extends eastward as a well-defined trough that, for a distance of about 4 miles, generally separates Jurassic (?) granitic intrusive rocks on the north from sedimentary and volcanic rocks of Tertiary and Quaternary age on the south. The Lava Mountains, which are visible to the southeast (east of Johannesburg), probably contain a northern extension of the Tertiary section that is exposed at Red Mountain. El Paso Peaks, to the northwest, are underlain by granitic rocks that are intrusive into the upper part of the Paleozoic section of El Paso Mountains.

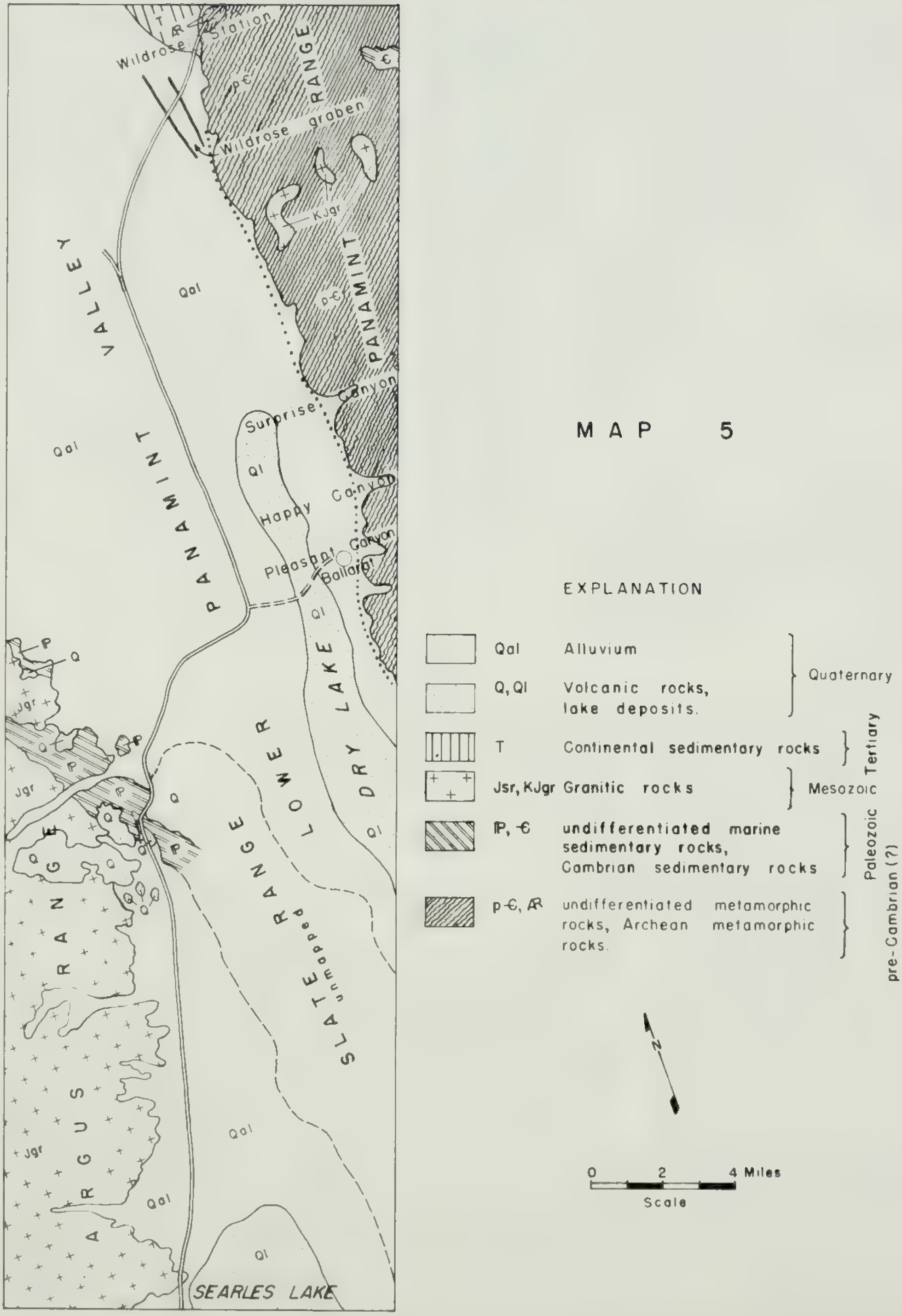
For the next 35 miles the rocks described in this road-log consist almost entirely of these granitic intrusive types and Quaternary rocks that locally cover them. Travel northward to the Searles Station turnoff and thence eastward (right) for 3.7 miles to the Johannesburg-to-Trona highway. Turn north (left) on this highway. The view from the south slope of Salt Wells Valley, about 8 miles from the road junction, encompasses the southwestern part of the Basin and Range province, which is characterized by mountain ranges that trend north to north-northwest. The Sierra Nevada, which border the Basin and Range province on the west, form the western skyline. The broad Indian Wells Valley, occupied by China Dry Lake, separates these mountains from the Argus Range toward which the road to Trona extends.

The white floor of the southern part of Searles Dry Lake can be seen to the northeast, across a south-trending spur of the Argus Range. Visible successively eastward from Searles Dry Lake are the Slate Range, Lower Panamint Valley, and the southern part of the Panamint Range, which is dominated by Telescope Peak, the high point on the eastern skyline. Most of the bedrock in the country west of Searles Dry Lake consists of granitic rocks of the Sierra Nevada batholith. The geological features of the Slate Range are incompletely known; and the many formations that comprise the Panamint Range are discussed in connection with points farther along the route.

In Pleistocene time, during intervals when the climate was much moister than it is now, the region noted in the preceding paragraph contained extensive lakes that lay along the course of the ancestral Owens River (Gale, 1915; Blackwelder, Contribution 5, Chapter V). Fed partly by this river and partly by streams from the bordering ranges, lakes formed in Owens Valley (to the northwest and not visible from the Salt Wells Valley area), Indian Wells Valley, Salt Wells Valley, Searles Valley, Panamint Valley, and Death Valley. The drainage from Indian Wells Valley flowed eastward through the notch in the hills that is marked by the white buildings, and thence down Salt Wells Canyon, which is occupied by the road to Trona.

During the latest of the moist intervals the Owens River extended only as far as Searles Valley, where it formed a saline lake about 16 miles long and 375 or more feet deep. Most of the detrital material gathered by the river south of Owens Valley is believed to have settled in China Lake, which occupied Indian Wells Valley. During the desiccation of Searles Lake in the dry period that followed, saline constituents crystallized to form a huge body composed mainly of various salts of sodium, potassium, and boron. This body underlies an area of about 32 square miles, and is about 71 feet in average thickness. Another body of salts, representing an earlier period of desiccation, is about 35 feet thick and is separated from the upper body by a 10- to 15-foot layer of mud.

In an earlier moist interval that probably preceded the formation of the lower crystal body, Searles Lake was more than 640 feet deep



MAP 5

EXPLANATION
Qal Alluvium
Q, Ql Volcanic rocks, lake deposits.
Quaternary
T Continental sedimentary rocks
Tertiary
Jsr, KJgr Granitic rocks
Mesozoic
₱, -Є undifferentiated marine sedimentary rocks, Cambrian sedimentary rocks
Paleozoic
p-Є, Ɐ undifferentiated metamorphic rocks, Archean metamorphic rocks.
pre-Cambrian (?)
N
0
2
4 Miles
Scale
Wildrose Station
Wildrose graben
RANGE
PANAMINT
KJgr
p-Є
Є
T
Ɐ
PANAMINT VALLEY
Qal
Surprise Canyon
Happy Canyon
Pleasant Canyon
Ballarat
Ql
DRY LAKE
LOWER
SLATE RANGE
unmapped
ARGUS RANGE
Jgr
P
Q
SEARLES LAKE

(Blackwelder, Contribution 5, Chapter V), and joined continuously with China Lake in Salt Wells and Indian Wells Valleys to the west. During this interval also Searles Lake overflowed into Lower Panamint Valley, which in turn overflowed into Death Valley by means of an outlet at Wingate Pass at the south end of the Panamint Range. Lake beds deposited at this time are exposed in Salt Wells Valley and are discontinuously exposed along Salt Wells Canyon. Low on the south slope of the valley the road crosses a belt of small tufa towers built on the lake bottom. They are most noticeable near the junction with the road to Ridgecrest.

Travel northwestward to the bottom of the valley and down Salt Wells Canyon, where patches of the Pleistocene lake beds lie upon Mesozoic granitic rocks. Shore terraces, cut by the latest lake to occupy Searles Valley, are exceptionally well preserved at the mouth of the canyon and along both the west and east margins of the valley. Five miles south of the highway is a remarkable group of calcarous tufa pinnacles, as much as 100 feet high, that rest on a gravel bar of this lake (Blackwelder, Contribution 5, Chapter V). When Searles Lake overflowed into Panamint Valley, the connecting stream extended eastward and northward around the south end of the Slate Range, which separates Searles Valley from Lower Panamint Valley.

The east face of the southern part of the Argus Range, which is first seen from the spur that is rounded by the highway before it trends northward along the margin of Searles Dry Lake, consists largely or wholly of Mesozoic granitic rocks. Half a mile northwest of the spur is the plant of the Westend Chemical Company, which since the mid-1920s has recovered soda ash and borax from the brine of Searles Lake (Wright, et al., 1953). The brine, as pumped from wells near the center of the lake, is recovered from the interstices of both the upper and lower crystal bodies.

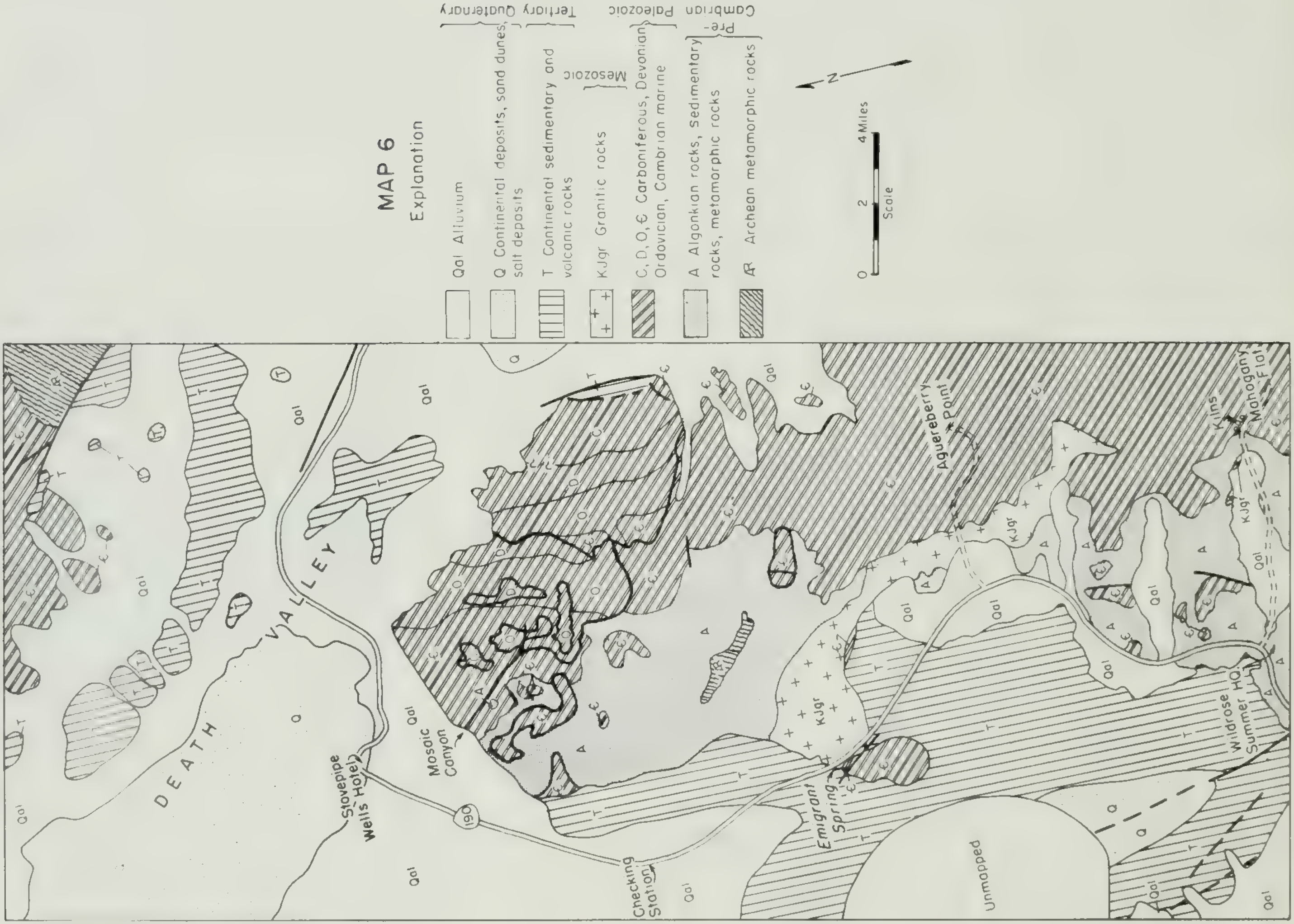
At the town of Trona, about 4½ miles farther north, Searles Lake brine also is treated. Here, at the plant of the American Potash and Chemical Company, are recovered various salts of sodium, potassium, boron, lithium, and bromine, as well as boric acid and liquid bromine. The treatment of brine at this locality was attempted as early as 1914, and, during World War I, the present operator developed a process for the extraction of potash that was the forerunner of one of the operations of the present plant. Brine from the lower body is treated by a carbonation process very similar to the one employed by the Westend Chemical Company and yields sodium carbonate and borax. Brine from the upper body is treated by a cyclic process, which involves the fractional crystallization of salt by heating, evaporation, and cooling, and yields potassium chloride, potassium sulfate, sodium carbonate, sodium sulfate, lithium carbonate, and bromine chemicals.

From Trona the highway extends northward and crosses the northern part of the Slate Range near its junction with the Argus Range (Map 5). From the quarry on the southwest slope of the Slate Range, about 1 mile to the east (right) of the highway, the Westend Chemical Company removes Paleozoic limestone, which is calcined at its Searles Lake plant to obtain carbon dioxide for the carbonation of the brine. Strata of probable Upper Paleozoic age, and granitic rocks that intrude them underlie most of the northern part of the Slate Range. These rocks are capped locally by Quaternary basalt, which is exposed in the roadcuts near the divide at the crest of the range.

From a turnout to the right and just north of the divide, one obtains a fine panoramic view of Lower Panamint Valley and the mountain ranges that bound it—the Argus Range on the west and the Panamint Range on the east. The steep west face of this part of the Panamint Range culminates in Telescope Peak, and is cut by numerous steep-walled canyons. The dirt road that extends eastward across the dry lake leads to the ghost town of Ballarat, at the east edge of the valley. The patch of green vegetation to the south (right) of the townsite marks the position of Post Office Spring, and lies at the mouth of Pleasant Canyon. The second canyon to the north of Pleasant Canyon is Surprise Canyon, which drains the southwestern slope of Telescope Peak. High in Surprise Canyon and hidden from this view is the site of the old silver mining town of Pamamint City. At the north end of the valley, the mouth of Wildrose Canyon can be seen in the area where the steep varicolored scarp is flanked by the uniformly gray hills.

Ballarat, which served as a miner's supply center, was most active in the 1890s, when its population was 400 to 500. The few remaining buildings now are occasionally inhabited by prospectors. Panamint City originated in 1873, when rich silver ore was discovered in upper Surprise Canyon, and it soon had a population estimated at 1,500. Within 2 years, however, a limited ore supply and smelting difficulties caused interest in the mines to slacken, and in July, 1876, a cloudburst destroyed the smelter and most of the buildings.

The steep western face of the southern Panamint Range is both a spectacular and puzzling feature. Although it generally is believed to be the scarp of a great fault along which the range was tilted eastward in Plio-Pleistocene time, the reason for the smoothness of much its lower slope is disputed. It has been suggested that this surface approximates the zone of faulting and hence has been little eroded (Maxson, 1950). Other investigators, in contrast, believe that it is mostly a surface of erosion whose strike parallels that of the fault zone, but whose dip is much less steep than that of the fault zone. Curry (cited by Maxson, 1950) has suggested that the Panamint scarp is a stripped sole of a warped thrust fault.


MAP 6
Explanation
Qal Alluvium
Q Continental deposits, sand dunes, salt deposits
Quaternary
T Continental sedimentary and volcanic rocks
Tertiary
KJgr Granitic rocks
Mesozoic
C, D, O, Є Carboniferous, Devonian, Ordovician, Cambrian marine
Paleozoic
A Algonkian rocks, Sedimentary rocks, metamorphic rocks
AR Archean metamorphic rocks
Pre-Cambrian
N
0
2
4 Miles
Scale
DEATH VALLEY
Stovepipe Wells Hotel
190
Mosaic Canyon
Checking Station
Emigrant Spring
Unmapped
Wildrose HQ Summer HQ
Aguereberry Point
Kilns
Mahogany Flat

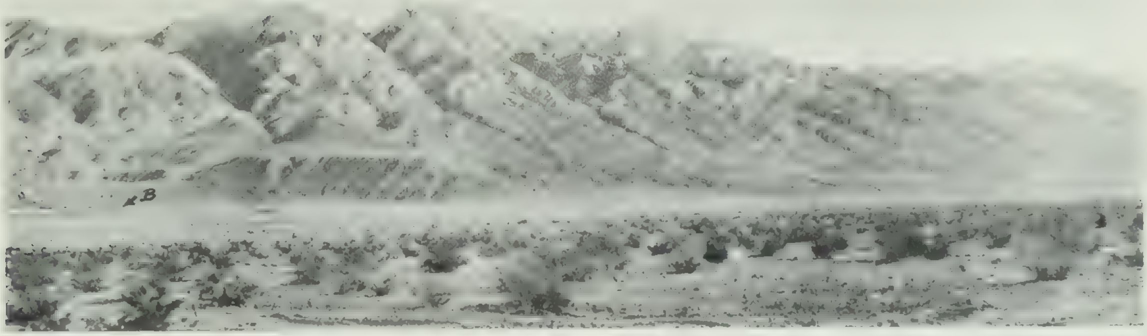


FIGURE 6. West face of Panamint Range viewed from Lower Panamint Valley. Remnant of old Quaternary alluvial fan extends from Pleasant Canyon (left). Steep face on this fan is a partly eroded fault scarp about 500 feet high. Traces of Pleistocene lake terraces faintly shown on upper parts of old fans. Old ghost town of Ballarat (B) at edge of more recent fan.

Whether or not the face approximates an actual fault surface, recent faulting along and near the west base of the range is clearly shown in the displacement of Quaternary alluvium (Maxson, 1950). Isolated patches of fanglomerate cling to bedrock above the base of the main scarp, and the alluvial fans are cut by scarps that lie parallel to the main scarp. An especially prominent fault scarp, about 500 feet high, truncates the large alluvial fan at the mouth of Pleasant Canyon (fig. 6). Displacement by this fault has caused the Pleasant Canyon drainage to cut deeply into the fan that it once deposited.

Under favorable conditions of lighting, wave-cut lake terraces can be seen on the upper surface of the Pleasant Canyon fan. The highest of these apparently were formed when Panamint Valley was filled to overflowing and drained eastward into Death Valley by way of Wingate Pass, which lies near the southern end of Lower Panamint Valley and has about the same elevation as the highest terrace.

The rocks in the part of the Panamint Range that is visible from the road on the northeast slope of the Slate Range have been studied only in a general way (Murphy, 1932; Sears, D. H., personal communication, 1954). This terrane is structurally complex, but it consists mostly of Lower Cambrian and pre-Cambrian metasedimentary rocks that dip eastward. It also contains bodies of intrusive rocks, some of pre-Cambrian age and others of Mesozoic age. The upper part of Telescope Peak is underlain by Lower Cambrian strata that include the Noonday dolomite and Johnnie formation. The belt of yellow and dark brown rocks low in the Pleasant Canyon area is believed to consist also of the Noonday dolomite (Johnson, B. K., personal communication, 1954). Pre-Cambrian metasedimentary rocks and various intrusive bodies form the remainder of this face of the range. Some of the larger intrusive bodies can be distinguished by their light gray color. Continue northward through Panamint Valley.

Wildrose Canyon to Furnace Creek Ranch

About 31 miles from Trona, at the junction of the road leading northwestward to Upper Panamint Valley, the route of this roadlog turns northeastward toward the mouth of Wildrose Canyon. The gray hills north of the canyon are underlain chiefly by moderately deformed fanglomerate of the Nova formation. This section has been designated as Miocene (?) in age (Hopper, 1947), but it closely resembles the Plio-Pleistocene Funeral fanglomerate of the Death Valley area and may be correlative with it. In the Wildrose Canyon area (Map 6) the Nova formation is unconformably underlain by unnamed older Tertiary sedimentary rocks, not more than 300 feet in maximum thickness, which in turn rest with depositional contact upon the pre-Cambrian rocks that lie south of the canyon.

Near the mouth of Wildrose Canyon a wide, down-faulted trench, commonly called the Wildrose graben, has been formed in Quaternary alluvium. This is one of the most striking examples of Recent deformation to be viewed along the route. The steep, nearly parallel

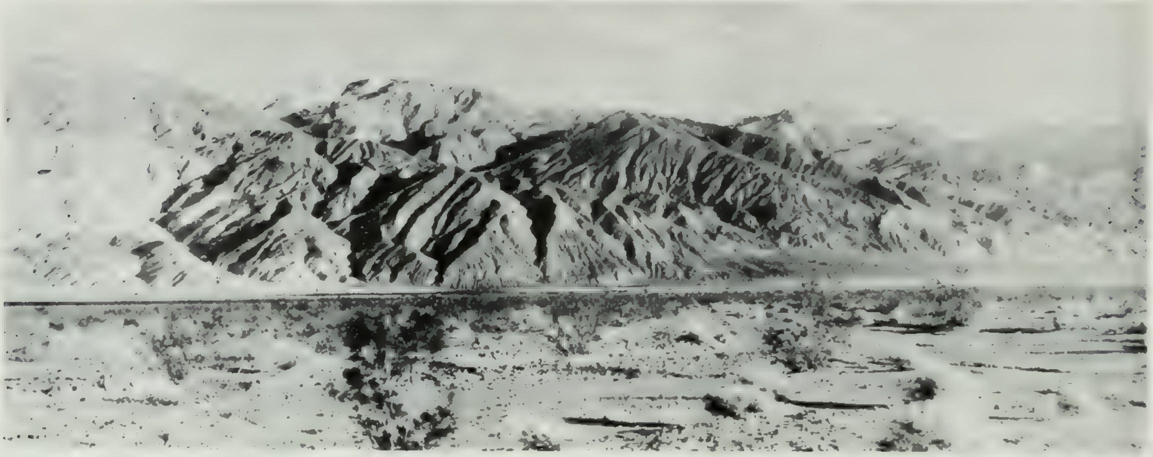


Figure 7. West face of Panamint Range north of part shown in figure 6. Smooth mountain front in center of photo may approximate plane of frontal fault. Note wine-glass canyons on this face. Bedrock consists mainly of pre-Cambrian crystalline rocks (dark) intruded by Mesozoic(?) granitic rocks (light) on left.

scarps that bound the graben are as much as 200 feet high, and show the beheaded channels of intermittent streams that formerly drained southwestward across the alluvial fan but since have been diverted southeastward along the floor of the graben. In approaching the graben from the west, the road follows one of these beheaded channels.

Well-exposed at the mouth of Wildrose Canyon are angular unconformities between the Nova formation and nearly horizontal Quaternary alluvium, and between the older Tertiary rocks and the pre-Cambrian rocks. The older Tertiary formation is distinguishable from the light gray Nova formation by its dark brown to orange color. It consists chiefly of mudstone, sandstone, and volcanic ash, and contains a thin basal member of fresh-water limestone.

From the base of the Tertiary section to the vicinity of the charcoal kilns, about 10 miles up the canyon to the east, the road traverses pre-Cambrian metasedimentary rocks that lie beneath the Noonday dolomite (lowermost Cambrian) (Sears, D. H., personal communication, 1954). These pre-Noonday rocks were first described by Murphy (1932), who assigned all but the highest (most easterly) units to two formations—the Panamint metamorphic complex and the Surprise formation. To these he tentatively assigned pre-Cambrian and Lower Paleozoic ages, respectively.

Apparently the oldest and most highly metamorphosed rocks in Wildrose Canyon are granitic gneisses and irregular granitic intrusive bodies that are exposed in a window in the vicinity of Wildrose Station. These rocks resemble the earlier pre-Cambrian (Archean) rocks of the southern Death Valley region, and have been tentatively correlated with them (Sears, D. H., personal communication, 1954). The window lies beneath contorted carbonate rocks that appear to mark the base of the thick overlying sequence of stratified rocks.

The lowest formation of this sequence dips eastward, and is exposed in the canyon walls for about 2¼ miles eastward from Wildrose Station. It is a monotonous unit composed mostly of mica schist and micaceous quartzite that commonly is conglomeratic. These rocks, although placed within the Panamint metamorphic complex by Murphy (1932), are less metamorphosed than at Wildrose Station and have been tentatively dated (Sears, D. H., personal communication, 1954) as later pre-Cambrian. Their total thickness is undetermined, but apparently is measurable in thousands of feet.

The base of the overlying Surprise formation (Murphy, 1932) lies just east of the Death Valley Monument summer headquarters, on the side-road to the charcoal kilns and Mahogany Flat. From the headquarters area Wildrose Canyon widens eastward into a broad, mature valley that appears to be a low-relief remnant of an erosion surface that was developed before the Plio-Pleistocene uplift of the

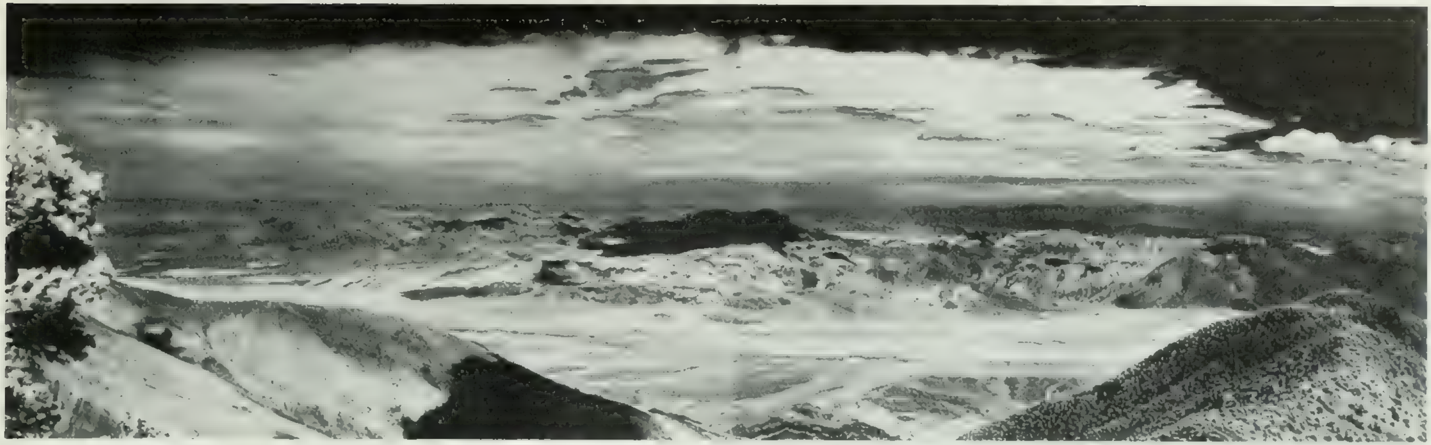


FIGURE 8. Eastward view of Death Valley from Mahogany Flat. Funeral Mountains (left) and Black Mountains (right) on opposite side of valley. Furnace Creek Ranch at extreme left on floor of valley. *Photo by Robert A. Cartter.*

Panamint Range (Maxson, 1950). The section exposed on both sides of this valley is broken by faults that apparently cause some of the strata to be repeated. In general, this area is underlain by east-dipping sedimentary rocks of later pre-Cambrian and Lower Cambrian ages, and these locally have been intruded by Mesozoic (?) granitic rocks.

A point on the road about 1¼ miles east of the headquarters, and opposite the radio relay station, affords an excellent panoramic view of the topographic and geologic features of upper Wildrose Canyon. From here the road extends southeastward toward a double peak on the skyline—Rogers Peak on the north and Bennett Peak on the south. In a general way, the geological units are outlined by the distribution of vegetation. The barren slopes on the skyline are underlain by shale and quartzite of the Lower Cambrian Johnnie formation, which is equivalent to the Hanaupah formation described by Murphy (1932). The tree-bearing belt, containing piñon pines and junipers and extending northward to the slopes of Wildrose Peak on the opposite side of the valley, marks the approximate extent of the Lower Cambrian Noonday dolomite, which here contains prominent quartzite members in addition to dolomite. Dark gray interlayered conglomerate, shale, quartzite, and limestone that belong mostly to the Surprise formation are exposed on the treeless area at the base of Wildrose and Rogers Peaks, as well as on the ridges that border both sides of the valley. The ridge on the north side of the valley is capped by two outliers of orange-colored Noonday dolomite, and low on its south flank is a belt of light-colored Mesozoic (?) acidic intrusive rocks.

The beehive charcoal kilns, about 6 miles farther up the road, were built during the period 1880-90 to supply fuel for a smelter at the Modoc lead-silver mine in the Argus Range, about 21 miles to the west. The kilns were in use for only a few years.

The various members of the Noonday dolomite cross the canyon bottom in the vicinity of the kilns. Mahogany Flat, on the crest of the Panamint Range, is reached by about 1½ miles of very steep road that extends beyond the kilns. The flat is noted for its fine stand of piñon pines and for the spectacular view of Death Valley that it affords (fig. 8). The Johnnie formation is exposed in cuts from about 1,000 feet south of the charcoal kilns to Mahogany flat.

Return to the main Death Valley highway and travel northeastward toward Emigrant Pass. Here the road also lies within the belt of later pre-Cambrian rocks. Visible from a point at the top of the grade and about 2½ miles from the summer headquarters are rounded hills on the western (left) skyline that consist of fanglomerate of the Nova formation. Patches of yellowish brown rocks of the Noonday dolomite cap most of the near hills to the east (right). From a point about a quarter of a mile beyond the top of the grade, Telescope Peak can be viewed to the southeast.

Roadcuts along another grade, about 5½ miles from the summer headquarters, expose conglomerate with elongate pebbles (fig. 9). This rock apparently has been much more highly metamorphosed

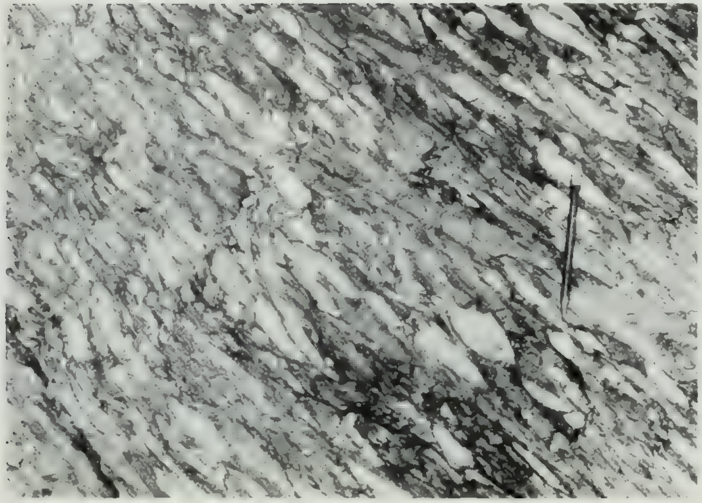


FIGURE 9. Exposure of pre-Cambrian stretched-pebble conglomerate on road between Wildrose Canyon and Harrisburg Flat.

than the later pre-Cambrian rocks in upper Wildrose Canyon, but it seems to be part of the Surprise formation (Sears, D. H., personal communication, 1954).

North of Emigrant Pass, the road traverses Harrisburg Flats, another low-relief remnant of the old erosion surface that is represented by upper Wildrose Canyon. From Harrisburg Flat an 8-mile side road leads eastward to Aguereberry Point, and affords a close inspection of a part of the north-striking Lower Cambrian section, as well as a superb view of Death Valley. One and a half miles from the turnoff, the Aguereberry Point road passes just north of the old townsite of Harrisburg, which existed briefly as a tent town following a gold strike in 1905. It was named after Shorty Harris, a prospector who has become an almost legendary figure in Death Valley history (Caruthers, 1951).

At the narrow mouth of the small canyon about half a mile east of Harrisburg, the road crosses a sill-like or laccolithic body of Mesozoic (?) quartz monzonite, which is exposed near the crest of the Panamint Range for a strike distance of about 12 miles. East of this body the road traverses units of the Noonday dolomite. The wider part of the canyon still farther east is flanked by quartzite and shale of the Johnnie formation, which is well exposed along the road as it swings southward into a small side canyon. From here to Aguereberry Point, on the crest of the range, the upper part of the Johnnie formation, the Stirling quartzite, and the Wood Canyon formation, all Lower Cambrian in age, are encountered successively. Aguereberry Point itself is underlain by the Zabriskie quartzite, a persistent marker near the top of the Wood Canyon formation.

As one looks eastward from Aguereberry Point down the east slope of the Panamint Range, he views successively higher formations in the Paleozoic section. On the near ridge are east-dipping carbonate strata of the Cadiz and Bonanza King formations, both of Middle Cambrian age.

The brilliantly colored, layered rocks on the opposite side of Death Valley are sedimentary and volcanic rocks of Tertiary age. These dip northeastward toward and beneath Furnace Creek Wash, which marks the boundary between the Black Mountains on the south and the Funeral Mountains on the north. The southern part of the Funeral Mountains consists of essentially the same Paleozoic formations that form the east slope of the Panamint Range. The Furnace Creek fault zone, a major structural feature, separates the Tertiary rocks of Furnace Creek Wash from the Paleozoic rocks of the Funeral Mountains. In the northern and central parts of the Black Mountains, Tertiary rocks rest upon earlier pre-Cambrian rocks, and the Paleozoic section is missing. As this section, which probably was about 25,000 to 30,000 feet thick, appears to have been eroded in late Mesozoic or early Tertiary time, the northern part of the Black Mountains apparently rose a comparable distance during this time interval. The geological features of this region will be viewed more closely later in the journey. Return to the main road and travel northward across Harrisburg Flats.

Another side road, which extends northeastward from the northern part of Harrisburg Flats, leads to Skidoo, an idle gold-mining camp that was most active during the period 1907-13. Its name is said to have been derived from the then-popular ''twenty-three skidoo'' expression, because the gold discovery was made on the twenty-third day of the month. Water for the camp and a gold mill was piped 22 miles northward from Panamint Canyon. The pipe was removed during World War I, but its location is still marked by scars on the mountain slopes. The mines of the Skidoo area have been developed along gold-bearing quartz veins in a northern extension of the same granitic body that is traversed by the Aguereberry Point road.

The granitic rock forms the eastern skyline as seen from the Skidoo turn-off, and is flanked on the west by fanglomerate of the Nova formation, which borders both sides of the road in the upper part of Emigrant Canyon. Note the southeast-dipping layer of white tuff in this area. The contact between the Nova formation and the underlying granitic rock is crossed by the road at a point about

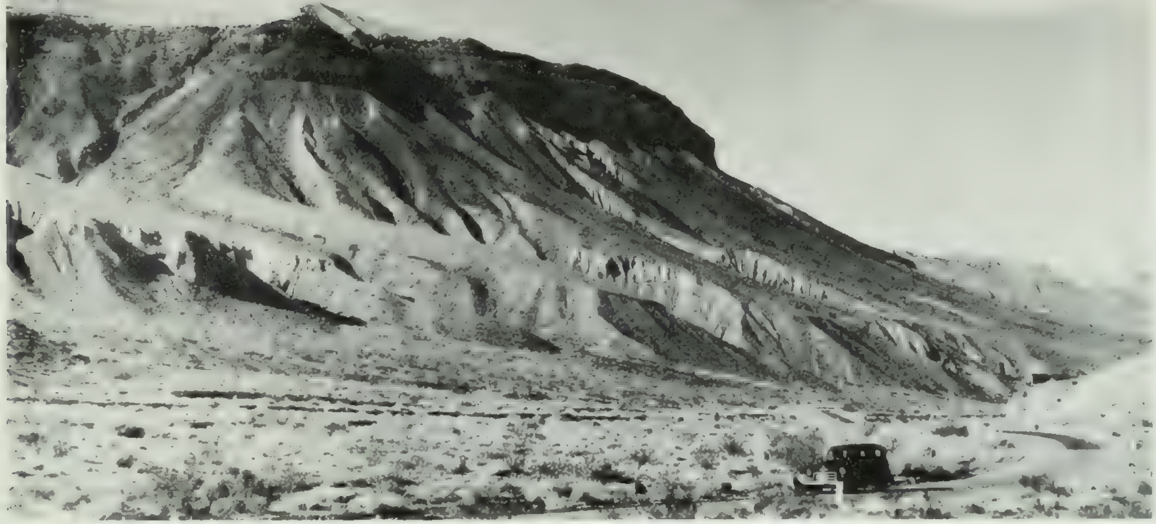


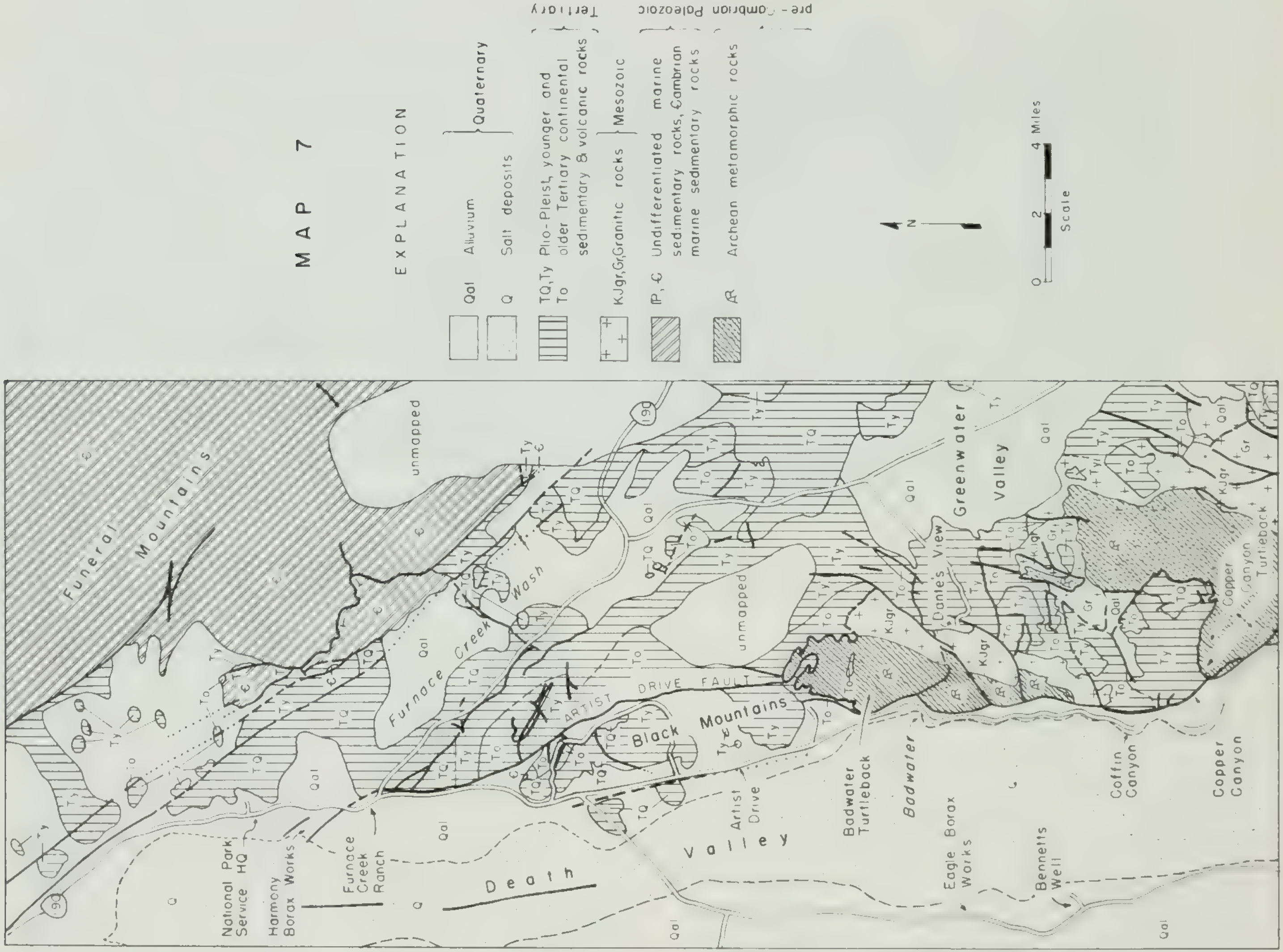
FIGURE 10. View of Tertiary Nova formation on west side of Emigrant Canyon below Emigrant Spring. Consists of fanglomerate with cliff-forming basalt flow high on canyon wall.

half a mile beyond the gold mill. In this area also, the Nova formation overlies highly fractured and brecciated Cambrian sedimentary rocks that border the granitic rocks on the west.

From the vicinity of Emigrant Spring northward, east-dipping basalt flows in the fanglomerate are exposed high on the west canyon wall (fig. 10). Also interbedded with the fanglomerate at the mouth of the canyon is a zone containing layers and lenses of monolithologic breccias derived from Paleozoic sedimentary rocks. A sedimentary origin for these bodies is indicated by their conformable contacts with the fanglomerate that enclosed them. Each lens appears to have formed as a debris flow, derived from brecciated source rock that generally was composed of a single rock type. Similar bodies of breccia, derived from a wide range of pre-Tertiary and Tertiary source rocks, occur in upper Tertiary and Quaternary sedimentary rocks in many parts of the Death Valley region. The monolithologic breccia bodies of Emigrant Canyon consits of one or another of the following rock types: dolomite, limestone, quartzite, phyllite, and schist. Carboniferous fossils are abundant in many of the clasts.

East of the junction of the Emigrant Wash road with State Highway 190, the steep west face of Tucki Mountain is flanked by a low belt of fanglomerate and basalt of the Nova formation. Tucki Mountain, although structurally complex in detail, consists in general of east-dipping later pre-Cambrian and Paleozoic strata that form what is probably the thickest and most complete pre-Tertiary section in the Death Valley region, if not in the entire State. As one travels northward and eastward around the north flank of the mountain, he can observe successively younger formations. The rocks on the west flank are largely later pre-Cambrian rocks equivalent to most or all of the pre-Noonday formations observed in Wildrose Canyon. However, the irregular masses of gray rock, which are most abundant low on the north and northwest flanks of the mountain face, consist of dolomite of the Middle Cambrian Bonanza King and Cadiz formations (L. F. Noble, personal communication, 1954). These masses lie against the mountain face, and exist as relatively thin, west-dipping slabs that apparently are blocks displaced by low-angle faulting.

The northern part of the Panamint Range can be seen to the north. Although this part of the range is not well known geologi-



MAP 7

EXPLANATION
Qal Alluvium
Q Salt deposits
Quaternary
TQ, Ty, To Plio-Pleist, younger and older Tertiary continental sedimentary & volcanic rocks
Tertiary
KJgr, Gr, Granitic rocks
Mesozoic
P, Є Undifferentiated marine sedimentary rocks, Cambrian marine sedimentary rocks
Paleozoic
Ꭿ Archean metamorphic rocks
pre-Cambrian
N
0 2 4 Miles
Scale
Funeral Mountains
unmapped
Furnace Creek Wash
ARTIST DRIVE FAULT
Black Mountains
Greenwater Valley
Dante's View
Copper Canyon Turtleback
Death Valley
National Park Service HQ
Harmony Borax Works
Furnace Creek Ranch
Artist Drive
Badwater Turtleback
Badwater
Eagle Borax Works
Bennetts Well
Coffin Canyon
Copper Canyon
190

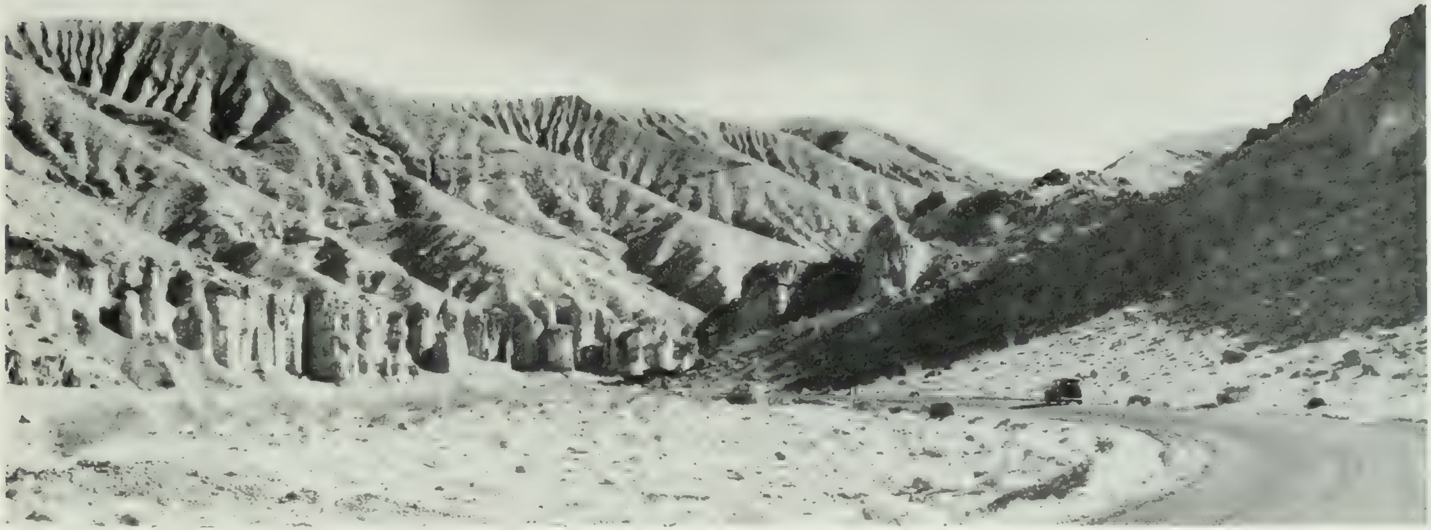


FIGURE 11. View southward of Nova formation at mouth of Emigrant Canyon. Resistant lenses of sedimentary origin that form low cliffs consist mostly of monolithologic breccia derived from Paleozoic formations.

cally, it consists mainly of Middle and Upper Paleozoic rocks. It apparently represents a structural element that is distinct from the southern part. Note the large size and total relief (3,000 to 4,000 feet) of the Quaternary alluvial fan that slopes eastward from the divide between the two parts.

From the vicinity of Stovepipe Wells resort, one looks southward at east-dipping later pre-Cambrian and Lower Cambrian strata on the north flank of Tucki Mountain. The yellowish-brown formation exposed just west of the mouth of Mosaic Canyon is the Noonday dolomite, at the base of the Lower Cambrian section. Successively exposed east of the canyon are Lower and Middle Cambrian strata of the Stirling quartzite, Wood Canyon formation (including the Zabriskie quartzite member that appears as a prominent pink stripe), Cadiz formation, and Bonanza King formation. The Johnnie formation, which ordinarily lies above the Noonday dolomite, here has been faulted out by a steeply dipping break whose trace approximately coincides with the canyon bottom.

Stovepipe Wells resort, a favorite stopping place for desert travelers, derives its name from a well in the area of sand dunes to the northeast and on the early trail between the mining camps of Skidoo and Bullfrog, Nevada. As the well commonly was covered by drifting sand, a stovepipe was driven in the sand to assist thirsty travelers in finding it. These dunes are modest in size, but are among the most photogenic of California's desert features.

From a point about 2.5 miles east of Stovepipe Wells, an additional and higher segment of the Tucki Mountain Paleozoic section can be seen. Between the ridges on the west and east are exposed Middle Cambrian to Lower Ordovician formations (Bonanza King, Racetrack, Nopah, and Pogonip). Note the west-facing fault scarp in the alluvium northeast of the mountain, and the Tertiary volcanic rocks in the low hills 3.0 miles east of Stovepipe Wells.

From these hills State Highway 190 trends eastward across the axis of the great Death Valley trough, a topographic and structural feature at least 150 miles long and perhaps much longer. Here the road points eastward to the vicinity of Daylight Pass, which divides the Grapevine Range on the north from the Funeral Mountains on the south. The part of the valley that lies north of the road is not described in this guide, and its geological features are less

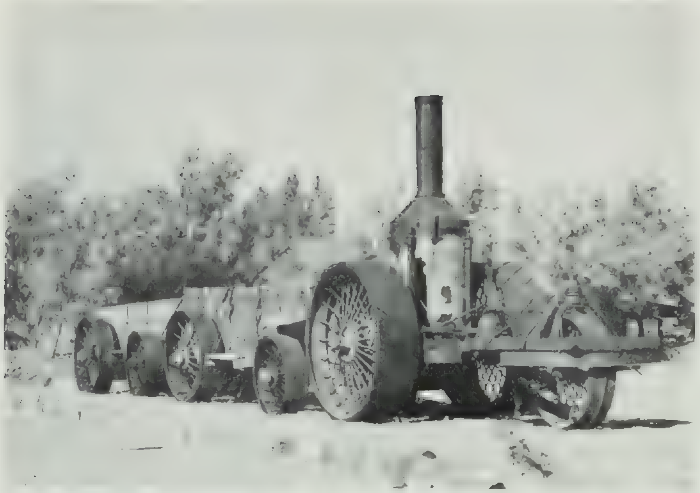


FIGURE 12. Wood-burning steam tractor at Furnace Creek Ranch. Unsuccessfully employed in attempt to replace 20-mule team in transportation of borax.

well known than those of the part to the south. Of especial interest in this northern area are the Ubehebe Craters and Death Valley Scotty's Castle. The craters are outstanding examples of volcanoes that develop explosively and eject very little volcanic rock. Such volcanoes, known as maars, characteristically have flat bottoms and inconspicuous cones.

Proceed along State Highway 190 southward along the east side of the valley to Furnace Creek Ranch (Map 7). In this area the highway traverses hills composed of deformed Tertiary sedimentary rocks that probably are part of the Mio-Pliocene (?) Furnace Creek formation. Although the hills are thoroughly dissected, they commonly are capped by Quaternary gravels that lie upon a nearly planar erosion surface beveling the Tertiary rocks. Both the Tertiary and Quaternary rocks are offset by northwest-trending faults of the Furnace Creek fault zone.

From Boundary Canyon southward to the area northwest of the lower part of Furnace Creek Wash, the west face of the Funeral Mountains is underlain by pre-Tertiary rocks that include metamorphic rocks of earlier pre-Cambrian (?) age, and Cambrian (?) sedimentary rocks. For about 18 miles southeast of Boundary Canyon, the base of the mountains coincides with the trace of Keene Wonder fault, which separates the pre-Tertiary rocks on the east from the Tertiary and Quaternary rocks on the west.

On the west side of the valley are the east-dipping Paleozoic strata that form the east slope of the Panamint Range. Tertiary volcanic rocks are exposed low along the spurs, and large alluvial fans head in the major canyons. The old Harmony Borax mill, which lies just east of the highway and near the lower end of Furnace Creek Wash, was constructed in 1882 near the site of the original discovery of borax in Death Valley. From this mill, the famous 20-mule team wagons hauled about 2½ million pounds of borax each year to Mojave, 165 miles away. Cottonball borax (ulexite) was gathered from the surface of the dry lake bed, dissolved, then crystallized in vats. The heat for dissolving the borax was supplied by burning mesquite that was gathered by the Indians. In the summer months, the high temperatures of Death Valley prevented the crystallization, and during this season the operations were transferred to the Amargosa Borax works south of Shoshone. The Harmony operation was suspended about 1890, when colemanite deposits were opened up near Calico, in western San Bernardino County.

Furnace Creek Inn and Furnace Creek Ranch are the largest resorts of the Death Valley area, and they form the major supply center for the Monument. Talks on the natural history of Death Valley are regularly scheduled at the ranch, and books on the area can be purchased here. Pamphlets and general information on the Death Valley area can be obtained at the Monument headquarters, about 3.1 miles north of Furnace Creek Ranch.

Side-Trip to Dante's View

Dante's View, a high point on the crest of the Black Mountains, affords a virtually unobstructed panorama of the entire length of Death Valley and the east slope of the Panamint Range. It is reached by traveling from Furnace Creek Inn 11 miles southeastward on State Highway 190, and thence an additional 13 miles south and west on a paved side road. For most of this trip the road follows Furnace Creek Wash, which trends southeast and is underlain by Tertiary and Quaternary rocks.

For about 10 miles southeast of Furnace Creek Inn, the wash separates the northern part of the Black Mountains on the southwest from the central part of the Funeral Mountains on the northeast, and northwest-dipping strata of the Mio-Pliocene (?) Furnace Creek formation and of the overlying Plio-Pleistocene (?) Funeral fanglomerate are exposed in the wash. Paleozoic sedimentary rocks, which compose the part of the Funeral Mountains that is visible from the wash, have been brought into contact with these formations and with Quaternary alluvium by the Furnace Creek fault zone, one of the major structural features of the Death Valley area. To the northwest this zone apparently joins with the Death Valley fault zone and the area between the two apparently was depressed in Tertiary and Quaternary time to receive sedimentary and volcanic rocks at least 13,000 feet in total thickness. Colorful and grotesquely eroded beds of siltstone and sandstone are prominent in this formation for about 8 miles in the lower part of the wash, and can be seen best from Zabriskie Point and the Twenty-Mule Team Canyon side road. The rilling and convexity of the hill slopes are characteristic of the weathering of fine-grained, poorly consolidated strata in an arid climate.

Just south of Zabriskie Point is an excellent example of stream capture. Here the headward development of Gower Gulch has resulted in capture of the Furnace Creek drainage. To the northeast of the highway are alluvium-capped terraces cut in rocks of the Furnace Creek formation.

The northern end of the Greenwater Range, as seen from the side road to Dante's View, consists essentially of borate-bearing beds of the Furnace Creek formation and a capping of upper Pliocene (?) basalt. The old mining camp of Ryan, which is owned by the Pacific Coast Borax Company, can be seen on the west slope of the range, and is reached by a short side road. The numerous mine workings in the Ryan area have been developed in borate deposits (principally colemanite) that occur as layers in the Furnace Creek formation. These mines were active in 1914-28, after which the company moved its operations to a deposit at Kramer, in Kern County.

In the upper part of Furnace Creek Wash are dissected Quaternary fanglomerates derived from the bordering ranges. As the road swings westward up the east slope of the Black Mountains, it passes from the fanglomerates into light-colored Tertiary volcanic rocks that probably are part of the Furnace Creek formation. The darker rocks on the skyline to the northwest of the road, which form the Dante's View promontory, are volcanic rocks of the Artist Drive formation (Oligocene ?). Here the two formations are in fault contact.

From Dante's View one can look to the Death Valley floor which contains the lowest points in the United States (282 feet below sea level). He can then look northwest to the distant skyline, and see the crest of Mt. Whitney, the highest point in the United States (14,495 feet).

The return to Furnace Creek Inn, by way of the same road, affords a distant view of the Paleozoic rocks that compose the central part of the Funeral Mountains. The prominent white band is the Eureka quartzite of Middle Ordovician age. Normal faults that cut these rocks cause some of them to be repeated.

Furnace Creek to Shoshone

For about 35 miles south of Furnace Creek Inn the route of this guide follows the road along the east side of Death Valley. For most of this distance the road lies close to the base of the bold and youthful west-facing escarpment of the Black Mountains. This escarpment, which is 4,000 to 6,000 feet high and virtually barren of vegetation, is one of the most scenic features of the Death Valley region. To the west Telescope Peak rises 11,331 feet above the floor of the valley and thus has the greatest relief of any single mountain in the United States.

The geological features of the Black Mountains are exceedingly complex and are not yet completely understood. As these features and the problems of their origin can be mentioned only briefly here, a familiarity with the more detailed discussions by Noble (1941), Curry (Contribution 10, Chapter II), and Noble and Wright (Contribution 7, Chapter IV) would add significance to this part of the route. Here one travels along the western margin of a great fault block, shaped in plan like a two-pointed wedge and including the Black Mountains, the Greenwater Range, and several north-trending ridges east of the southern end of Death Valley.

This wedge, which is about 80 miles long and 25 miles in maximum width, is bounded by two major fault zones—the Death Valley fault zone on the west and the Furnace Creek fault zone on the east. The wedge appears to have been raised many thousands of feet between these two fault zones, as the thick section of pre-Tertiary sedimentary rocks that once covered it appears to have been partly to wholly removed during the mid-Mesozoic to mid-Tertiary interval. The thickness of this cover probably was in the range of 25,000 to 45,000 feet. The most abundantly exposed rocks are those of an earlier pre-Cambrian metamorphic complex.

In general the northern and central parts of the Black Mountains consist of a core, composed of metamorphic rocks (earlier pre-Cambrian) and intrusive igneous rocks (earlier pre-Cambrian to Tertiary), that is discontinuously flanked and locally capped by masses of rocks of a wide range of types and ages.

Most of the masses show a very complex internal structure, and are composed of irregular blocks and breccia bodies that range in length from a few feet to thousands of feet. In the northern part of the Black Mountains they consist almost entirely of Tertiary sedimentary and volcanic rocks such as those seen from the road to Dante's View. In the central part, later pre-Cambrian and Paleozoic sedimentary rocks also are abundant, and earlier pre-Cambrian metamorphic rocks are locally present in the masses that overlie the core. They ordinarily rest with fault contact upon the core.

The surface of the core is characteristically smooth and little eroded, and has the form of broad, plunging anticlines and synclines. As the anticlines resemble turtle carapaces in shape, the name "turtlebacks" has been applied to them (Curry, 1941). Three turtlebacks have been recognized in the Black Mountains, and can be viewed along the route of travel. Each plunges northwestward, and the western flank of each dips gently to moderately toward the valley.

The disordered masses that overlie the turtleback surfaces have been interpreted as remnants of one or more thrust sheets that have been largely eroded from the cores. The surface of thrusting is believed to have been thrown into broad folds by a warping of the core of the range. The origin of these structural features, however, is still a perplexing problem whose solution awaits additional detailed study.

The western flank of the Black Mountains is cut by numerous steep-walled canyons at whose mouths are almost perfectly formed alluvial fans and cones. These fans contain a much smaller volume of material than the huge coalescing fans, as much as 3,000 feet in relief, that extend eastward from the Panamint Range. The notable difference in volume of modern fan detritus suggests that the Black Mountains escarpment is the younger of the two, and the difference in the degree of erosion shown by the two mountain fronts is compatible with this age relation. Also, the Panamint fans are being dissected, whereas the Black Mountains fans are not.

The fans along both sides of the valley contain linear scarps that are roughly parallel to the bordering mountain fronts. Most or all of these are fault scarps, although some may be attributable to differential compaction of the alluvium. Normal faulting of much greater magnitude occurs along the western margins of the turtleback surfaces, and along the intervening parts of the mountain front. Recurrent uplift along these normal faults has caused many of the canyons to be wineglass-shaped in cross section.

Travel southward from Furnace Creek Inn along the east Death Valley road. A very fresh-appearing scarplet breaks the alluvium on the east (left) side of the road for a mile or more south of its junction with State Highway 190. The mountain front east of here exposes northeast-dipping strata of the Furnace Creek formation, which are separated from the alluvium of the valley floor by the Artist Drive normal fault. About 4.5 miles from the junction, basalt of late Pliocene (?) age lies west of the fault and is exposed in the low hills along the road. These hills show terraces cut by the waters of Lake Manly, the most extensive of the Pleistocene lakes that occupied Death Valley. Crude artifacts found on one of these terraces suggest that human beings dwelled there when the lake stood at that level (Clements and Clements, 1953).

An improved dirt road, which branches southwestward at a point 6 miles from Furnace Creek Inn, extends along the west side of Death Valley to rejoin the east road about 37 miles farther south. Of particular interest along this western route are the site of the Eagle Borax works, the grave of Shorty Harris, and Bennetts Well. In 1849 the Bennett party, a group of pioneers seeking a short cut to the gold fields of California, was suffering from privation when a halt was made at the spring now known as Bennetts Well. They camped here while William L. Manly and John Rogers continued on foot to find a route of escape from the valley. These men made an heroic round trip in 26 days, and they then led the party to safety. The words "good-bye, Death Valley" are reliably reported to have been said by one of the departing group, and the valley was thus named.

Eagle Borax works was the first borax plant constructed in Death Valley, but it was operated only during the more temperate months of 1881 and 1882, and never was commercially successful.

Much of the thick section of brilliantly colored Tertiary volcanic and sedimentary rocks that form the northern part of the Black Mountains can be seen to the east of the junction of the two Death Valley roads. The lower part of the main mountain front southeast of Mushroom Rock is underlain by the Artist Drive formation (Oligocene ?), which is composed of sedimentary and volcanic rocks. The low hills in the foreground are underlain mostly by strata of the Furnace Creek formation that have been dropped against the Artist Drive formation along the Artist Drive fault.

Artist Drive loop, the entrance of which lies 4.3 miles south of Mushroom Rock, is a scenic drive through the foothills of the Furnace Creek formation to exposures of the Artist Drive formation along the scarp of Artist Drive fault. A small natural bridge in fanglomerate of the Artist Drive formation is reached by a 1-mile side road about 2.4 miles south of the southern Artist Drive turnoff. Less than a mile south of the natural bridge, the Artist Drive formation butts into the northwest-plunging nose of the Badwater turtleback. From the head of the natural bridge road, one has an excellent view of the smooth west flank of this turtleback (fig. 13). Note the wineglass-shaped canyon cut into this flank.

For many years the small pool of saline water at Badwater, which lies at 280 feet below sea level, was believed to mark the lowest point in the United States, but recent topographic mapping by the U. S. Geological Survey has established two lower points, both on the floor of Death Valley and both at an elevation of 282 feet below sea level. These lie 3½ miles northwest and 4 miles west of Badwater.

In the vicinity of Badwater, and elsewhere along the west face of the Black Mountains, patches of Quaternary alluvium, similar to

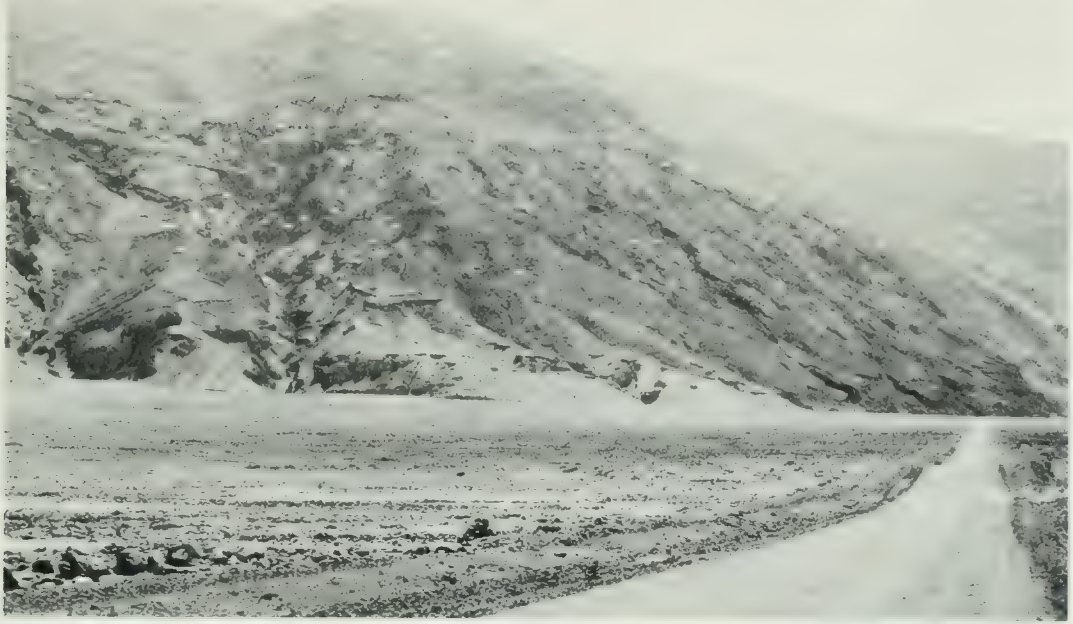


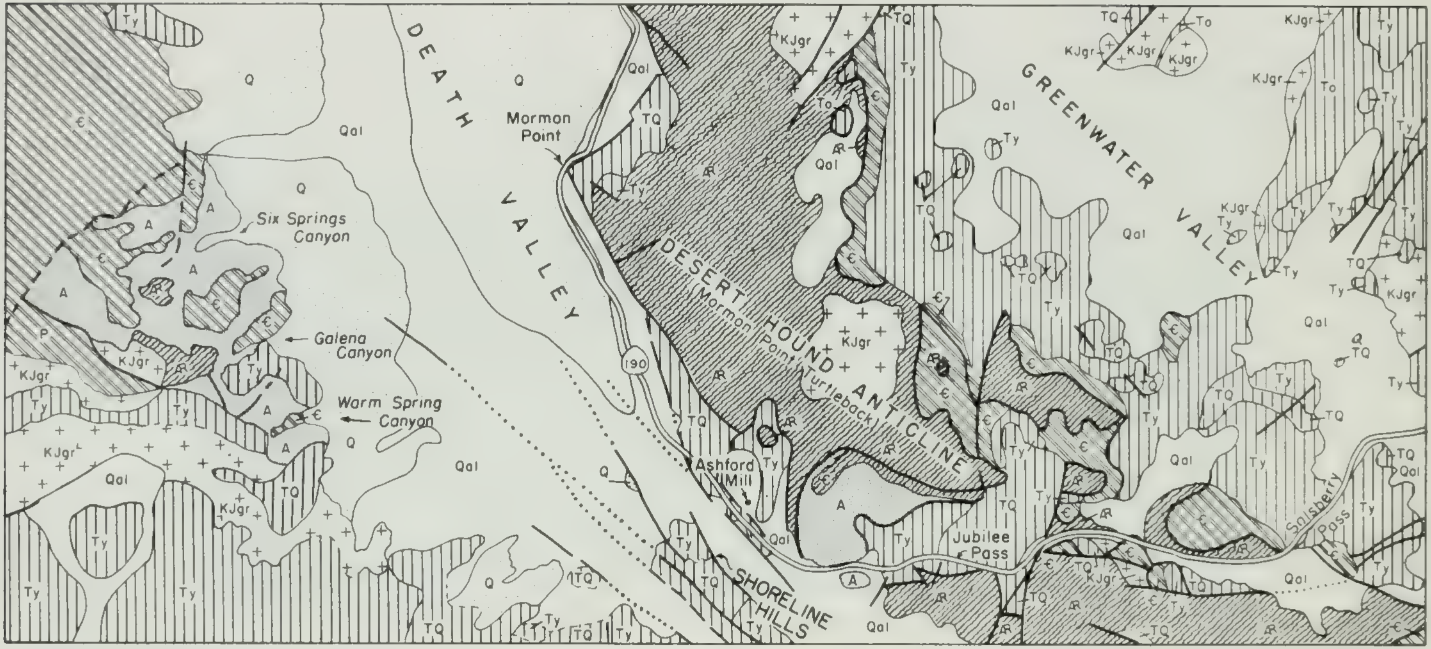
FIGURE 13. View southward of west surface of Badwater turtleback. Underlain mostly by earlier pre-Cambrian gneiss. Patches of Quaternary alluvium cling to bedrock above valley floor.

those observed on the west face of the Panamint Range, cling to the bedrock above the present alluvial surface.

A quarter of a mile south of Badwater, the Badwater turtleback surface trends obliquely southwestward into the Black Mountains, and for an airline distance of about 7½ miles, between Badwater and the mouth of Copper Canyon, the mountain front is underlain by large blocks that are greatly disordered and brecciated. Some of these blocks consist of pre-Cambrian (?) igneous and metamorphic rocks, and others consist of Tertiary volcanic and sedimentary rocks. The mountain front here is the eroded scarp of a major normal fault. The trace of this fault coincides with the break in slope between the scarp and the bordering fans. Two Recent scarplets that offset the alluvium are prominent in the first fan southwest of Badwater, and probably are subsidiary to the frontal fault. This part of the Black Mountains, one of the most precipitous slopes of the California desert region, contains several wineglass-shaped canyons. The fans that border it are almost perfectly symmetrical in plan.

Copper Canyon drains an embayment that is underlain by a relatively undeformed, east-dipping section of Tertiary sedimentary and volcanic rocks. These have been correlated chiefly with the Furnace Creek formation (Noble, 1941), and the strata in one area contain animal tracks tentatively dated as Pliocene (Curry, 1941). Along their southern border these Tertiary rocks butt with fault contact against earlier pre-Cambrian gneiss. This contact marks the northern and northeastern margin of the Copper Canyon turtleback, the nose of which plunges northwestward and extends beneath Quaternary alluvium and Tertiary rocks at a point southeast of the mouth of Copper Canyon. To the south, the similarly plunging nose of the Mormon Point turtleback, which also is composed of earlier pre-Cambrian gneiss, can be seen at Mormon Point about 4½ miles southwest of tne Copper Canyon area.

The lower part of the main mountain mass between the two turtlebacks is underlain by pre-Cambrian (?) diorite. The low hills that flank the mountain mass consist of sandstone and fanglomerate, and



MAP 8

Explanation

▭ Qal Alluvium }Quaternary
▭ Q Continental, salt deposits and volcanic rocks }Quaternary
▥ TQ, Ty, To Plio-Pleistocene, younger and older Tertiary continental sedimentary and volcanic rocks. }Tertiary
⊞ KJgr Granitic rocks }Mesozoic
▧ P, € Permian and Cambrian marine }Paleozoic
▭ A Algonkian metamorphic rocks }Pre-Cambrian
▨ Ѧ Archean metamorphic rocks }Pre-Cambrian

0 2 4 Miles
Scale

N

form an embayment between Mormon Point and the southwest flank of the Copper Canyon turtleback. These sedimentary rocks are but slightly deformed, and are correlative with the Funeral fanglomerate. They are in fault contact with the older rocks and are broken by several fault scarps, the most prominent of which extends for about a mile southward from Mormon Point and borders the highway on the east. The surface at Mormon Point is marked by shore terraces that were cut by the waters of Lake Manley.

Westward and southwestward from Mormon Point (Map 8) is a distant view of the general geological features of the southeastern part of the Panamint Range. The most prominent formation is the Noonday dolomite (Lower Cambrian), which is grayish yellow, dips gently eastward, and caps the lower slopes of the range like icing on a cake. It unconformably overlies dark-colored sedimentary rocks and diabase of the later pre-Cambrian Crystal Spring formation, the lowest unit of the Pahrump series. These are the most westerly of the known exposures of the Crystal Spring formation.

North of Six Spring Canyon the Noonday dolomite is overlain by dark-colored strata that probably are correlative with the Johnnie formation (Lower Cambrian). At the southern end of the range Mesozoic (?) granitic rocks intrude the Paleozoic and earlier pre-Cambrian rocks. Dark-colored Tertiary volcanic rocks form most of the Panamint mass south of the most southerly large canyon, and extend into the Wingate Wash area between the Panamint Range and the Owlshead Mountains. They rest mainly on Mesozoic granitic rocks, and thin northward. Wingate Wash marks the position of a syncline in the Tertiary volcanic rocks. The overflow of the Pleistocene lake that once filled Panamint Valley drained eastward through Wingate Wash into Lake Manly.

Six Spring Canyon generally is believed to lie on the route first followed in 1849 by Manly and Rogers, and later by the survivors of the Bennett party whom they led from the valley. The 20-mule teams, used in the 1880s to haul borax from the Harmony borax works 165 miles to Mojave, skirted the east side of the valley and left it by way of Wingate Wash.

Today human activity in the southeastern Panamint Range centers about talc mining. Several large deposits of commercial talc have formed as alterations of dolomite of the Crystal Spring formation, and occur at or near contacts with bodies of pre-Cambrian diabase. The principal workings are the Grantham (Warm Spring) mine in Warm Spring Canyon and the Death Valley mine in Galena Canyon.

From the vicinity of the Ashford mill site, one can look southward at the Owlshead Mountains, which are composed mainly of Mesozoic

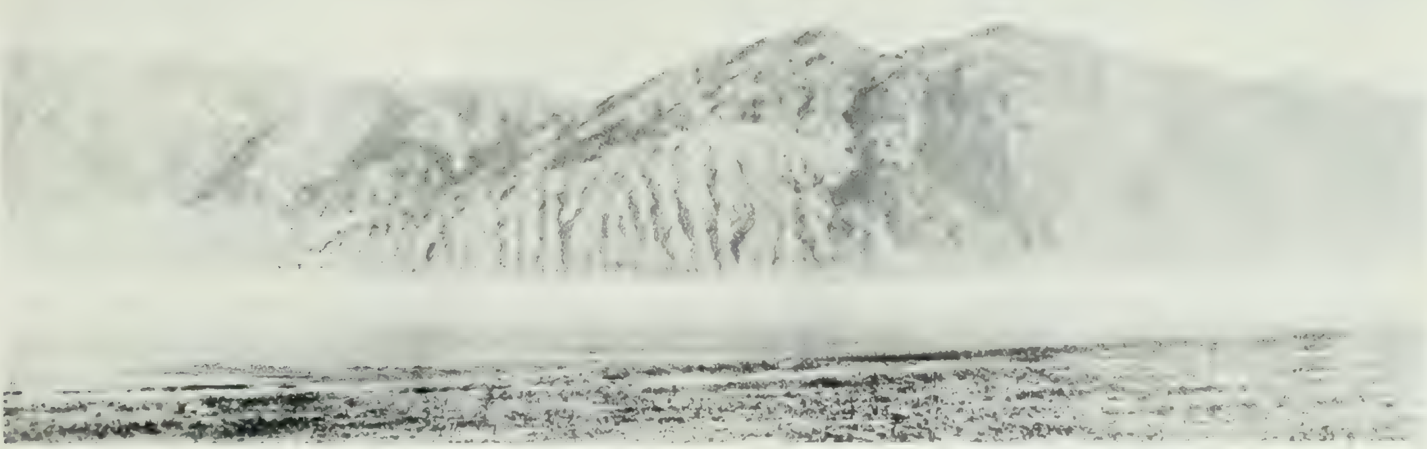


FIGURE 14. Mormon Point turtleback in Black Mountains viewed from west side of Death Valley. Youthful character of mountain is shown by slight dissection, hour-glass canyons, and small size of alluvial fans.

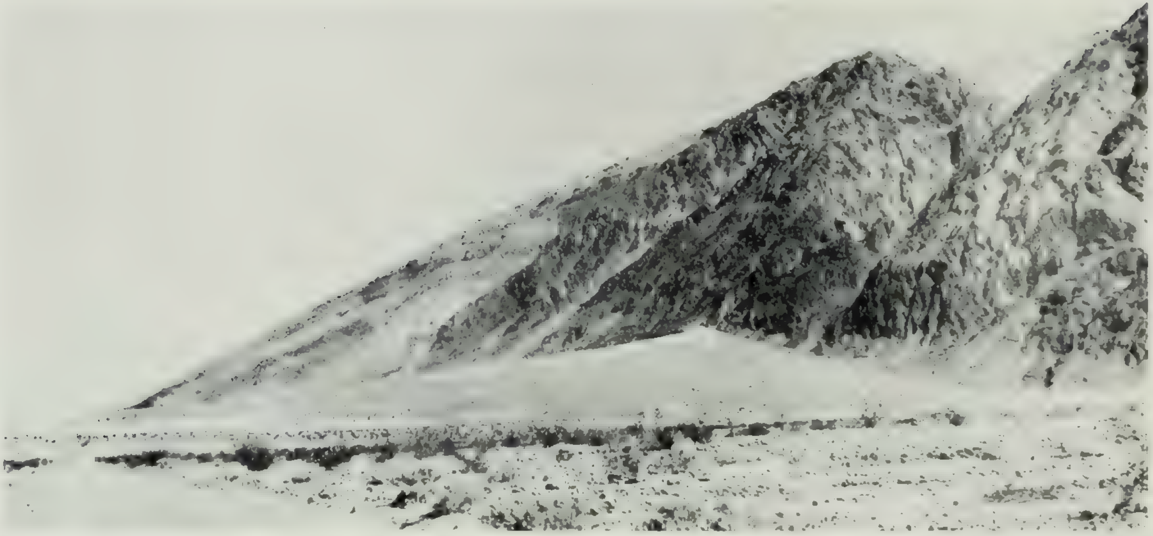


FIGURE 15. Small, perfectly formed alluvial fan at base of Black Mountains, south of Mormon Point.

(?) quartz monzonite. It has an intrusive contact with northward-dipping strata of the Crystal Spring formation, which form the north flank of the range. This formation is easily distinguished here by the black color of diabase sills hundreds of feet thick. Dark-colored Tertiary volcanic rocks locally cap the crest of the mountains. The badlands in the Confidence Hills, along the east side of the Owlshead Mountains, have been carved mainly in sandstone and siltstone of Tertiary age.

The Mormon Point turtleback (fig. 14), by far the largest turtleback in the Black Mountains, extends from the Mormon Point area southeastward for about 13 miles to the Virgin Spring area, where it has been termed the Desert Hound anticline (Noble, 1941). Unlike the Badwater and Copper Canyon turtlebacks, it is a doubly plunging feature. Southeast of Mormon Point, the highway parallels the west flank of the Mormon Point turtleback. Faulted and tilted Funeral fanglomerate (Plio-Pleistocene) lies between the highway and the mountain front. It contains basalt flows exposed in an aligned group of black hills that are bordered on the southwest by a fault scarp.

Shoreline Hill (fig. 15), a mile southwest of the site of Ashford mill and beyond the Amargosa River channel, also consists of basalt. It is flanked by lower hills of Funeral fanglomerate. This hill derives its name from the numerous well-developed shore terraces cut upon it by the waters of Lake Manly. The fanglomerate on each side of the Amargosa River channel generally dips toward the channel, which approximates the axial trace of a syncline (Noble, 1941).

In the Virgin Spring area, east and northeast of the Ashford mill site, structural features of the "turtleback" or "folded thrust fault" type were studied and first described in detail by L. F. Noble (1941). Here he named the principal fault surface the "Amargosa thrust." As in the area to the north, the fault separates an autochthonous block, composed of earlier pre-Cambrian metamorphic rocks and various igneous bodies, from overlying and irregularly distributed masses, many of which appear to be remnants of a thrust sheet. The overlying masses consist of blocks and lenses that are so diverse in composition and generally are so disordered in appearance that the term "Amargosa chaos" has been applied to them by Noble. He has subdivided the Amargosa chaos into three phases: (1) the Virgin Spring phase, composed almost entirely of blocks of later pre-Cambrian and Cambrian units, and ordinarily oriented in a crude eastward-dipping imbricate structure; (2) the Calico phase, a mosaic of fault blocks composed of brilliantly colored Tertiary volcanic rocks, intricately broken up but not everywhere entirely chaotic; and (3) the Jubilee phase, another mosaic of blocks and breccia layers. About half of the Jubilee phase is composed of granite breccia and Tertiary conglomerate, and the other half is composed of various Tertiary sedimentary rocks, Cambrian and later pre-Cambrian sedimentary rocks, later pre-Cambrian diabase, and earlier pre-Cambrian gneiss.

In the Virgin Spring area, as mapped by Noble (1941), all of the occurrences of the Virgin Spring phase of the chaos overlie the autochthonous block and are separated from it by the Amargosa thrust. The Calico and Jubilee phases rest mostly on the Virgin Spring phase. Their displacements by thrusting are probably much less than that of the Virgin Spring phase, and they appear to have been emplaced near the end or following the major movement on the Amargosa thrust. The breccia masses of the Jubilee phase are now believed to be largely of debris-flow origin.

As one travels southeastward from the Ashford mill site and thence eastward on the Shoshone-Death Valley highway, he skirts the southern flank and southeastward-plunging nose of the Desert Hound anticline. Ashford Peak, which lies east and northeast of the mill site, is underlain by the thickest occurrence of the Virgin Spring phase of the Amargosa chaos. Here the blocks that compose the chaos are less disordered than in most other areas of exposure. Sedimentary units of the Pahrump series, apparently in their proper stratigraphic order, underlie the main mountain front. The orange, red, and yellow dolomite and purple shale, low on the mountain, belong to the Crystal Spring formation, and the higher olive gray rock is the Beck Spring dolomite. Grayish yellow Noonday dolomite (Lower Cambrian) caps the mountain. These units dip eastward and butt northward against gray earlier pre-Cambrian gneiss that occupies the core of the Desert Hound anticline. The Amargosa thrust, which marks the contact, dips gently to moderately southward.

A southern projection of this large mass of Virgin Spring chaos lies just south of the Shoshone-Death Valley highway from half a mile to 1½ miles east of the road junction. The most westerly exposures consist of dolomite and chert of the Crystal Spring formation, and those to the east are of Beck Spring dolomite.

For the next 1½ miles, the low hills nearest the road are underlain by rocks of the Jubilee phase of the chaos, which appears to lie in a structural basin and to rest mostly upon Virgin Spring chaos. Here the Jubilee phase consists of red conglomerate of Tertiary age, together with lenses of breccia composed of granitic rock, various volcanic rocks, and older pre-Cambrian and Cambrian sedimentary rocks. A fault contact between the Jubilee phase and later pre-Cambrian gneiss to the south can be seen clearly from a point about 2 miles east of the road junction. The red Tertiary conglomerate is well exposed on the prominent point about three-quarters of a mile farther east.

From the grade just west of Jubilee Pass is an especially fine northwestward view of the southwest flank of the Desert Hound anticline, the trace of whose axis lies about on the skyline and passes through Desert Hound Peak, the high point on the ridge. The brightly colored rocks that border the ridge are part of the same mass of Virgin Spring chaos observed earlier from the Ashford mill site. The contact between them and the underlying earlier pre-Cambrian gneiss marks an eastward continuation of the Amargosa thrust.

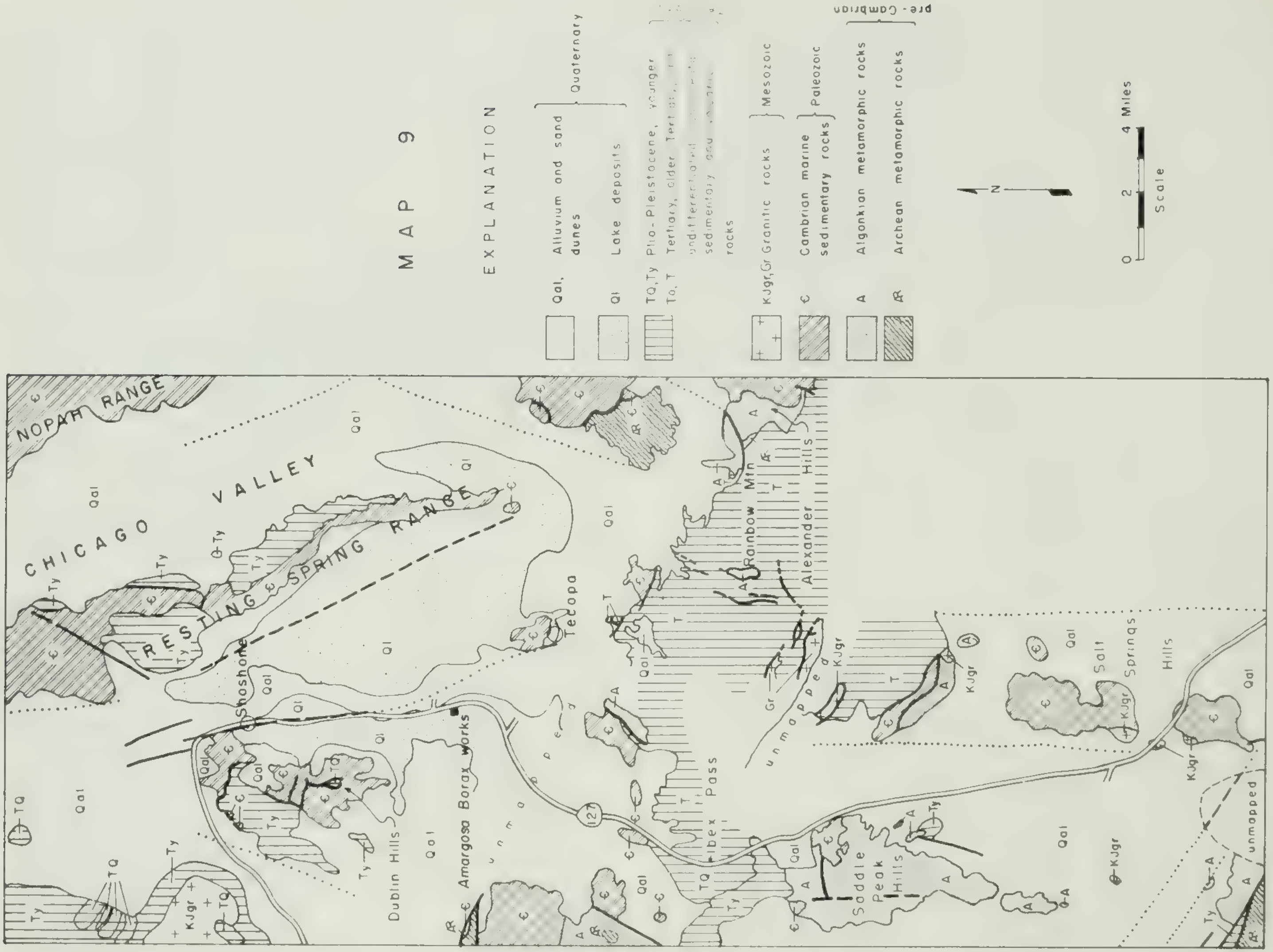
Slightly deformed Funeral fanglomerate, containing interbedded basalt flows, lies with depositional contact upon all three phases of the Amargosa chaos. It occurs in a belt that extends about 4 miles northward from the vicinity of Jubilee Pass. It is well exposed at the pass, and lies north and northwest of the road for about 2 miles beyond the pass. The southeast-plunging nose of the Desert Hound anticline extends beneath the fanglomerate, but shows no expression in it, thereby indicating that the fanglomerate was deposited after development of the anticline. Indeed, the fanglomerate appears to have been localized in an irregular structural trough produced by the folding.

As one travels eastward and down-grade from Jubilee Pass, the gray mountain front before him and across Graham Wash consists almost entirely of earlier pre-Cambrian metamorphic rocks, mostly granitic gneiss. A diabase dike (later pre-Cambrian ?) cuts these ancient rocks on the northwest nose of the mountain. The brilliantly colored ridge on the skyline to the north and northeast is underlain mostly by Tertiary volcanic rocks that form the Calico phase of the Amargosa chaos. Epaulet Peak is distinguished by a black capping of younger basalt.

Excellent exposures of the Amargosa thrust near the southeast-plunging nose of the Desert Hound anticline can be seen from an unimproved but passable road that extends up Virgin Spring Canyon. The exposures lie at a distance of 1½ to 3 miles from the junction of this road with the Death Valley—Shoshone Highway, and this junction is 1¼ miles east of Jubilee Pass.

The only roadside exposure of the Amargosa thrust along the main route of this guide is about 3 miles east of Jubilee Pass. Here earlier pre-Cambrian gneiss appears low on the cliff south of the road, and is overlain by elongate blocks of Cambrian and later pre-Cambrian rocks, principally dolomite, quartzite, jasperoid chert, and diabase. At the contact the gneiss is thoroughly crushed through a thickness of several feet.

Continue northeastward to Salsberry Pass. Volcanic rocks similar to those of the Calico phase of the Amargosa chaos underlie both



MAP 9

EXPLANATION
Qal, Alluvium and sand dunes
Ql Lake deposits
Quaternary
TQ,Ty To, T Plio-Pleistocene, younger Tertiary, older Tert undifferentiated sedimentary and rocks
KJgr,Gr Granitic rocks
Mesozoic
€ Cambrian marine sedimentary rocks
Paleozoic
A Algonkian metamorphic rocks
Ar Archean metamorphic rocks
pre-Cambrian
N
0 2 4 Miles
Scale
NOPAH RANGE
CHICAGO VALLEY
RESTING SPRING RANGE
Shoshone
Tecopa
Rainbow Mtn
Alexander Hills
Salt Springs Hills
Dublin Hills
Amargosa Borax works
Ibex Pass
Saddle Peak Hills
unmapped
127
Qal
Ql
Ty
TQ
T
KJgr
Gr
€
A
Ar

FIGURE 16. Shoreline Hill, at south end of Death Valley, showing strands cut by Pleistocene Lake Manly in Pliocene(?) basalt.

peaks that flank the pass—Salsberry Peak to the northwest and Sheephead Mountain to the southeast. The descent from Salsberry Pass affords a northwestward view of Greenwater Valley, which is bordered on the west by the Black Mountains and on the east by the Greenwater Range. Patches of late Pliocene (?) basalt, which occur along both sides of the valley, dip toward its center and indicate that the valley coincides with a syncline that was developed at least partly during Quaternary time. The southern end of the Greenwater Range consists of a dome of granitic rock that is discontinuously flanked by masses of basalt. These patches of volcanic rocks dip away from the dome and suggest that it is a deformational rather than an erosional feature.

From the gentle, southwest slope of Greenwater Valley, the view northeastward, along the trend of the highway, includes the Dublin Hills (Map 9) in the right foreground, the Resting Spring Range farther east, and the Charleston Mountains of Nevada on the distant skyline. As viewed southeastward, the dissected white beds of Pleistocene Lake Tecopa outline the southern end of the Amargosa Valley. Tecopa Hot Springs and the town of Tecopa lie on the far side of the lake beds. Behind and to the left of Tecopa is the southern end of the Nopah Range, which joins southward with the Alexander Hills. The Kingston Range forms the skyline to the left of the Alexander Hills.

The west part of the Dublin Hills consists of Tertiary volcanic rocks, and Cambrian sedimentary rocks underlie the eastern part of the hills. These rocks can be seen south of the road as it extends eastward to join State Highway 127 in Amargosa Valley. The steep west face of the Resting Spring Range, which forms the east border of this part of the valley, consists entirely of Cambrian strata. The mine workings at the base of the range, which can be seen from the road as it descends into Amargosa Valley, are in borate-bearing Tertiary sedimentary rocks that probably are correlative with the Furnace Creek formation. Also to be seen along this part of the road are the most northerly exposures of the nearly horizontal lake beds that were deposited in Pleistocene Lake Tecopa. Turn south (right) on State Highway 127 and travel southward through Shoshone.

Shoshone to Baker

Shoshone is a small desert settlement supplied with water by warm springs at the east base of the Dublin Hills. It was formerly a station on the Tonopah and Tidewater Railroad, but since the removal of the railroad tracks in 1941, Shoshone has flourished as a stopping point for tourists and prospectors, and as a supply center for nearby mines.

Badland exposures of the Tecopa lake beds lie about Shoshone and are traversed by State Highway 127 for a distance of about 11 miles southward. Lake Tecopa, which occupied an irregular basin about 15 miles in diameter, was fed by the south-flowing Amargosa River and had an outlet just south of the settlement of Tecopa. A downcutting of the outlet led to the draining of the lake and to the present state of dissection of the lake beds. The exposed beds consist mostly of siltstone with subordinate layers of volcanic ash and bentonite clay. Most of the numerous trenches on the hills were made during World War I by the U.S. Geological Survey as part of an intensive but unsuccessful search for commercial concentrations of nitrates.

From the turnoff to Tecopa, about 5 miles south of Shoshone, one can look across the lake and northeastward to the southern end of

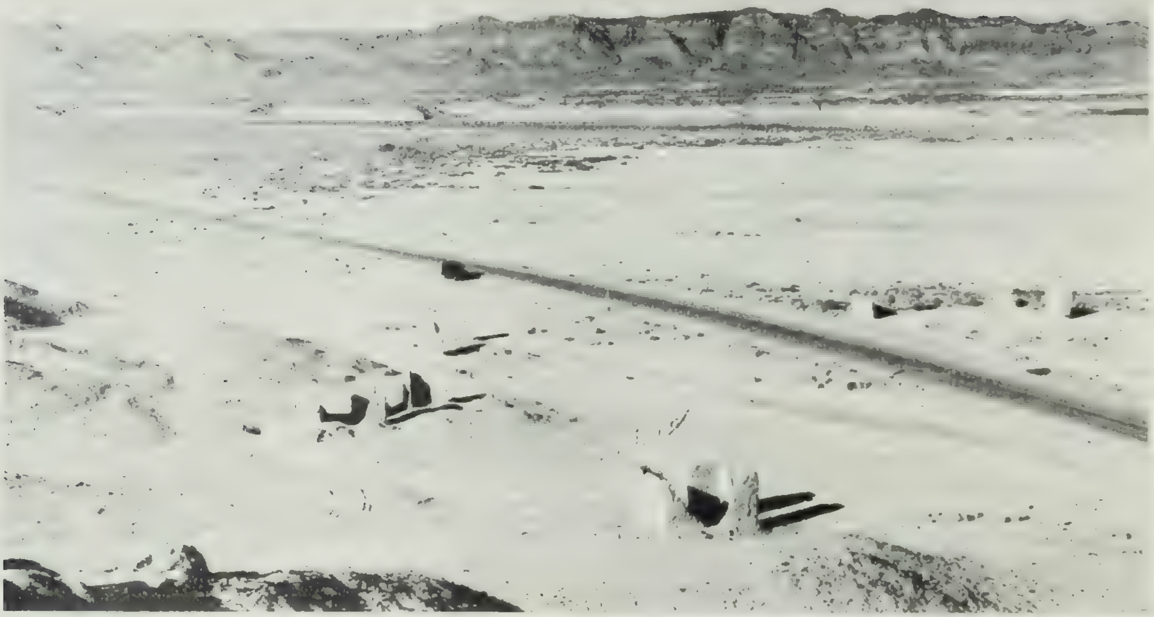


Figure 17. View northeastward across Amargosa Valley to southern part of Resting Spring Range. Valley underlain by dissected, nearly horizontal beds of Pleistocene Lake Tecopa. Stripped face of range consists of east-dipping Cambrian formations. Ruins of Amargosa borax works in foreground.

the Resting Spring Range. The Nopah Range lies parallel to and east of the Resting Spring Range. Both are east-tilted fault blocks. The hills behind the Tecopa hot springs consist of strata of the Lower Cambrian Stirling quartzite.

At the southern end of the Nopah Range, the dark hill with the triangular profile consists of earlier pre-Cambrian gneiss. Lower Cambrian Noonday dolomite, which forms the base of a 23,000-foot, east-dipping section of Paleozoic sedimentary rocks (Hazzard, 1937), overlies gneiss on the east side of the hill. At the south end of the Alexander Hills these two units are separated by a 7,000-foot section of later pre-Cambrian rocks of the Pahrump series. A northward transection of the Pahrump formations by the Noonday dolomite is attributable partly to an angular unconformity and partly to thrust faulting.

The remains of the Amargosa borax works (fig. 17) lie on State Highway 127 about eight-tenths of a mile south of the turnoff to Tecopa. As noted above, these were active during summer seasons in the period 1882-90, as the summer heat in Death Valley caused a suspension of the operation at the Harmony works. The nearest prominence south of the Amargosa borax works is McLain Peak, which consists chiefly of east-dipping Lower Cambrian strata (Noonday dolomite and Wood Canyon formation). The peak is flanked on the east by a section of Pliocene (?) fanglomerate, several thousand feet thick.

Another side-road to Tecopa joins State Highway 127 about 2 miles southwest of the borax works. A turnout near this junction affords a westward view of the northern part of the Ibex Hills. On the skyline to the north are the highly colored Tertiary volcanic rocks of Sheephead Mountain. These are in fault contact with earlier pre-Cambrian gneiss which forms the crest of the hills for about 5 miles south of the mountain. The varicolored rocks that compose the east flank of this part of the Ibex Hills consist of east-dipping imbricate slabs of later pre-Cambrian and Lower Cambrian strata. These slabs are part of the Virgin Spring phase of the Amargosa chaos and the contact between them and the underlying gneiss marks the trace of an extension of the Amargosa thrust.

Seen from Ibex Pass near the Inyo-San Bernardino County line, the southern part of the Ibex Hills forms the prominent skyline to the west and consists mostly of units of the Pahrump series (later pre-Cambrian) which dip steeply eastward toward the viewer. These rocks are part of the block that lies beneath the Virgin Spring chaos in the northern part of the Ibex Hills. The crest of the hills is underlain by a quartzitic member at the base of the Crystal Spring formation. Successively younger units occur lower on the slope. The prominent black band is a diabase sill along which deposits of commercial talc have formed as alterations of carbonate strata adjacent to the diabase. The diabase sill and the talc bodies are confined to the Crystal Spring formation. The low spurs near the base of the hills contain exposures of the Beck Spring dolomite (gray) and Noonday dolomite (tan).

Ibex Pass lies between low hills composed mainly of debris derived from Paleozoic and pre-Cambrian sedimentary rocks and from granitic rocks of undetermined age. This material apparently is part of a Pliocene (?) fanglomerate, several thousand feet thick and perhaps equivalent to the Funeral fanglomerate. Within the fanglomerate in this vicinity are layers of monolithologic breccia similar to those observed in the Nova formation at the mouth of Emigrant Canyon. Poorly sorted clasts of granitic rock compose virtually all of the material in the road cuts just south of Ibex Pass.

The area of low relief south of Ibex Pass extending for a distance of about 4 miles, is underlain by fanglomerate and by Tertiary volcanic rocks.

The Saddle Peak Hills (fig. 18), which lie west (right) of the road, consist of a thick section of rocks of the Pahrump series and are capped by tan masses of Noonday dolomite. The red strata that unconformably underlie the dolomite are part of the Kingston Peak

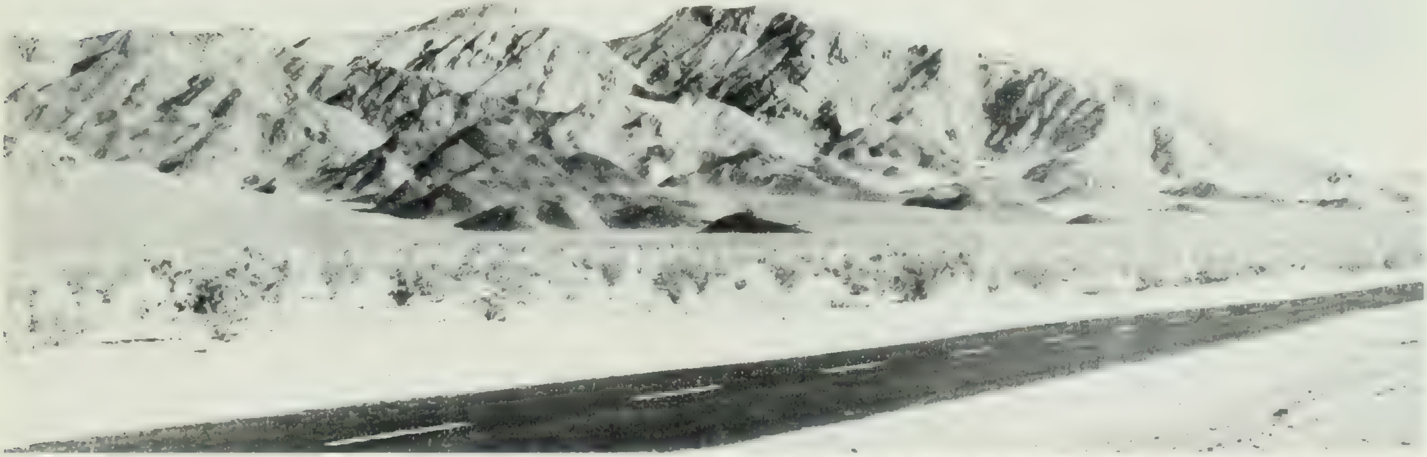
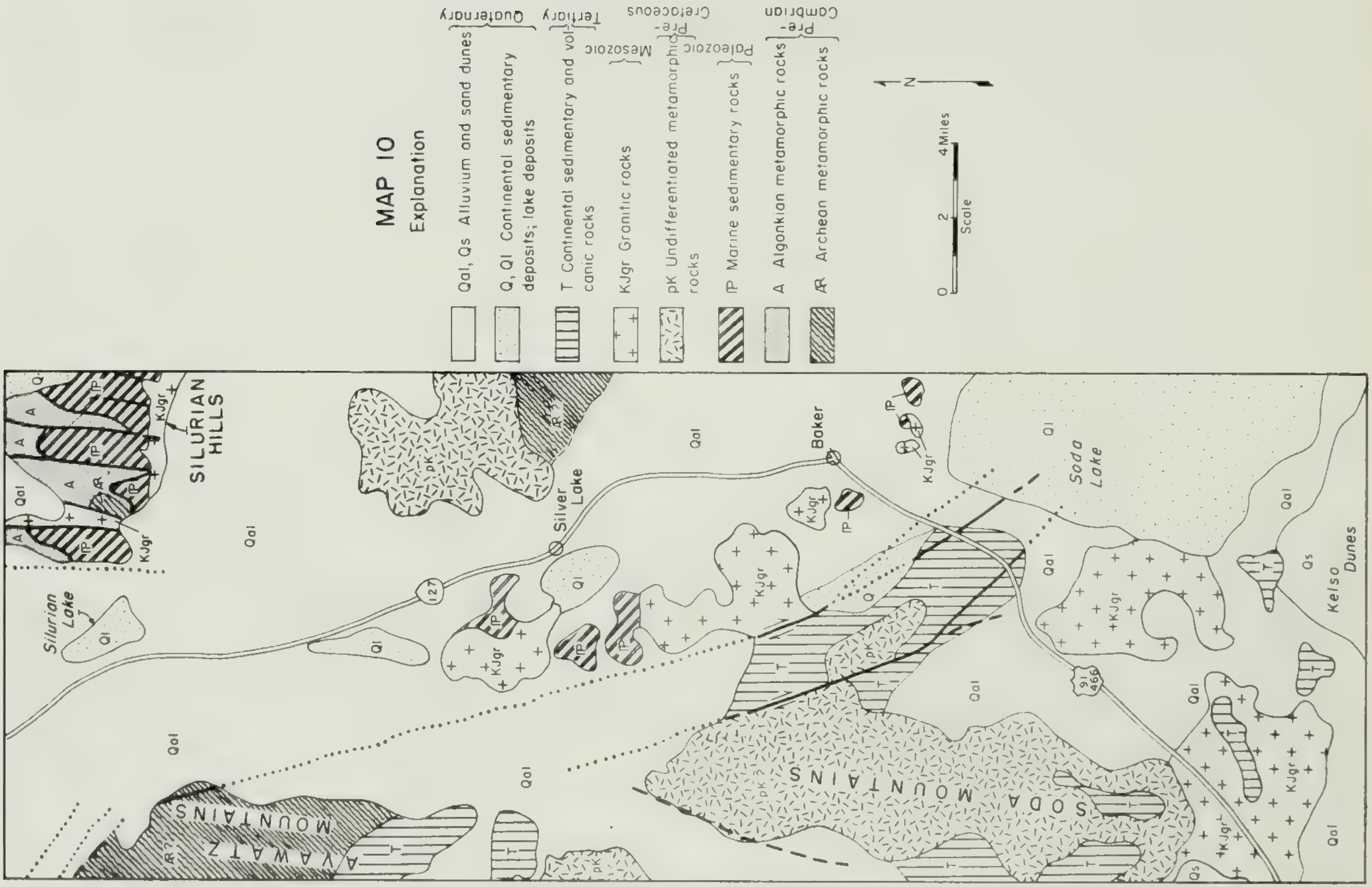


FIGURE 18. View northwestward at Saddle Peak Hills from State Highway 127. East-dipping strata of later pre-Cambrian Kingston Peak formation (dark) are capped by Lower Cambrian Noonday dolomite (light).



MAP 10

Explanation

Qal, Qs Alluvium and sand dunes
Q, Ql Continental sedimentary deposits; lake deposits
Quaternary
T Continental sedimentary and volcanic rocks
Tertiary
KJgr Granitic rocks
Mesozoic
pK Undifferentiated metamorphic rocks
Pre-Cretaceous
IP Marine sedimentary rocks
Paleozoic
A Algonkian metamorphic rocks
AR Archean metamorphic rocks
Pre-Cambrian
N
0 2 4 Miles
Scale
SILURIAN HILLS
Silurian Lake
Silver Lake
Baker
127
Soda Lake
Kelso Dunes
91 466
SODA MOUNTAINS
AVAWATZ MOUNTAINS
Qal
Ql
Q
Qs
T
KJgr
pK
IP
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AR

formation. The road trends southeast around the northeast flank of the Saddle Peak Hills, thence straight across the south end of Death Valley. Low in the valley the road crosses the channel of the Amargosa River which flows through here only during the winter and spring months. This river drains southward through Amargosa Valley, and then follows a semi-circular course to drain westward and northward into Death Valley.

The high west-trending range on the south skyline and to the right of the road is the Avawatz Mountains, flanked on the north, northeast, and east by prominent alluvial fans. The north to northeast face of the Avawatz Mountains is underlain by earlier pre-Cambrian metamorphic rocks and various intrusive rocks. The base of the north face approximately coincides with one of the major branches of the Garlock fault zone. Near the mouth of Sheep Creek this branch is joined by the Death Valley fault zone, which extends southeastward from the center of Death Valley.

The low north-trending hills east (left) of the road, which lie athwart of the Death Valley trough, are the Salt Springs Hills. They are underlain by east-dipping Lower Cambrian strata of the Johnnie formation, Stirling quartzite, and Wood Canyon formation, and by Mesozoic granitic intrusive rocks. The gap which the highway follows through these hills probably once lay on the course of the Mojave River when it flowed northward into Death Valley.

For about 2 miles southeast of the gap in the Salt Spring Hills, State Highway 127 points toward the Silurian Hills (Map 10), which border Silurian Dry Lake on the east. The low hills that form the skyline between the Kingston Range on the north and the Silurian Hills on the south are separable into three linear groups. The lower, western group are klippen of foliated pre-Cambrian rocks that rest unconformably on Tertiary sedimentary rocks. The middle and higher group are part of a thick bed of Tertiary monolithologic breccia. The third group, not visible from the west, are klippen of crystalline rocks. The klippen are remnants of a thrust plate 5 to 8 miles in diameter (Hewett, D. F., personal communication, 1954).

The Silurian Hills (Kupfer, Map Sheet 19) also are very complex structurally. In general, they consist of plates of Paleozoic (?) carbonate rocks that have been thrust over a highly disordered chaos of later pre-Cambrian sedimentary rocks and diabase. The hills also are cut by a group of north-trending, high-angle faults that post-date the thrusting. The eastward view across Silurian Dry Lake shows the foothills, between the viewer and main hills, which are underlain by southwest-dipping Paleozoic rocks. Most of the west slope of the Silurian Hills proper consists of rocks of the Pahrump series that overlie earlier pre-Cambrian metamorphic rocks exposed low along this base of the hills. On the southern (right) part of this face these rocks are overlain by a thrust plate composed of steeply dipping Paleozoic strata.

The low hills that lie east of the highway and extend south of the Silurian Hills for about 12 miles consist largely to wholly of the Halloran complex of early pre-Cambrian (?) metasedimentary and intrusive rocks as defined by Miller (1946). Other low hills that extend along the west side of Silver Lake from the power line crossing to Baker form the northeastern part of the Soda Mountains. These mountains are bordered on the west by a major fault zone that trends about N. 20° W. and is aligned with faults that lie along the east base of the Avawatz Mountains (L. T. Grose, personal communication, 1954).

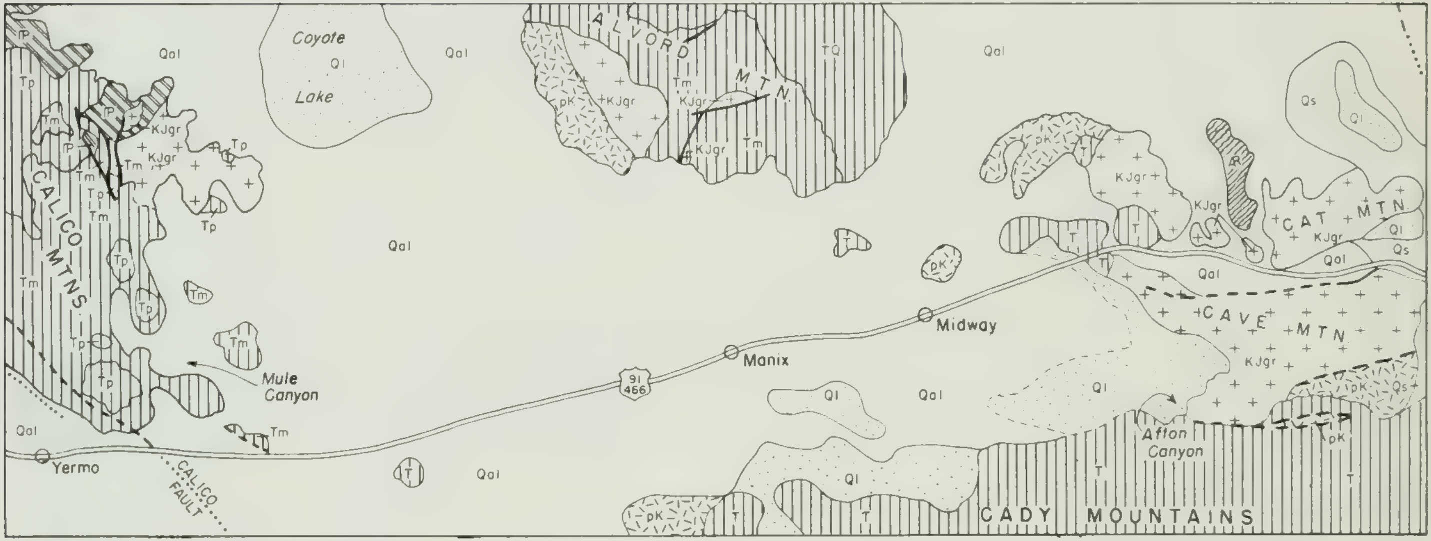
The most northerly of these hills is underlain by buff-colored dolomite of lower Paleozoic (?) age and by late Mesozoic (?) quartz diorite in which the dolomite occurs as a pendant. The dolomite is highly deformed but is not appreciably altered. The next hill southward and the hills flanked with wind-blown sand consist of metasedimentary rocks, chiefly quartzite and limestone, that probably are late pre-Cambrian or lower Paleozoic in age (L. T. Grose, personal communication, 1954). They are cut by low-angle thrust faults which generally dip southward. The thrust plates have been cut by a north-trending system of vertical faults. The remaining exposures of bedrock between Silver Lake and Baker consist principally of Mesozoic (?) intrusive rocks that range in composition from granite to gabbro.

Baker to Barstow

Most of the hills and mountain ranges that border U.S. Highway 91 between Baker and Barstow, are underlain by Mesozoic (?) granitic rocks in which metamorphic rocks, probably both pre-Cambrian and Paleozoic in age, are preserved as large pendants and septa. In general, nonmarine sedimentary rocks of Tertiary and Quaternary age underlie the basins and lower hills.

Baker is on the north side of Soda Lake, which is a remnant of the Pleistocene Lake Mojave; it is now a sink of the Mojave River, whose headwaters are in the San Bernardino Mountains near Cajon Pass. The most northerly flow of the river in historic time has been into Silver Lake, north of Baker. During some of the Pleistocene glacial stages the river probably flowed into southern Death Valley.

The Providence, Granite, and Bristol Mountains, listed from east to west, form the skyline south of Baker. The prominent sand dunes southwest of Soda Lake, which are about 500 feet high, probably are composed mostly of material transported into the region by the Mojave River and thence carried to the dune area by prevailing west winds. Strong cross winds move the material back and forth across the valley. The hill north (right) of the highway and just west of Baker



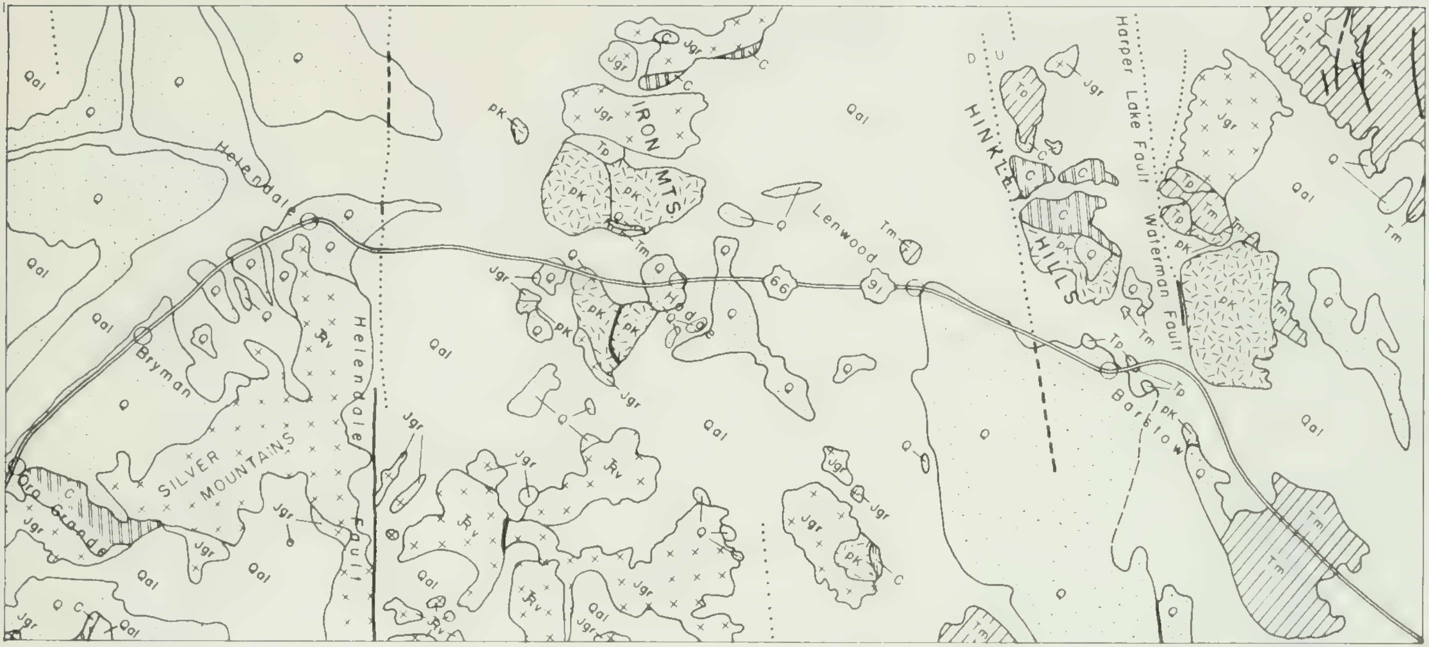
MAP II

Explanation

☐	Qal, Qs Alluvium and sand dunes	Quaternary
░	Ql Lake deposits	Quaternary
▥	TQ, Tp, Tm, T Plio-Pleistocene, Pliocene, Miocene, and undifferentiated continental sedimentary and volcanic rocks	Tertiary
⊞	KJgr Granitic rocks	Mesozoic
▧	ⱣP Marine metasedimentary rocks	Paleozoic
▨	pK Undifferentiated metamorphic rocks	Pre-Cretaceous
▨	ƎR Archean metamorphic rocks	Pre-Cambrian

0 2 4 Miles
Scale

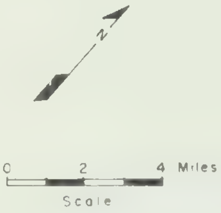
N



MAP 12

EXPLANATION

☐	Qal	Alluvium	Quaternary
☐	Q	Continental sedimentary deposits	Quaternary
▥	Tm, Tp	Miocene and Pliocene continental sedimentary and volcanic rocks	Tertiary
☐	Jgr, Ћv	Granitic rocks, metavolcanic rocks	Mesozoic
▨	pK	Undifferentiated metamorphic rocks	pre-Cretaceous
▧	C	Carboniferous marine sedimentary rocks	Paleozoic



consists of a jumble of limestone and dolomite that is mostly, if not wholly, of Carboniferous age. For the next 14 miles, the highway crosses the southern end of the Soda Mountains, which here are underlain by Mesozoic (?) granitic rocks. From 5 to 12 miles southwest of Baker moderately deformed Pliocene (?) fanglomerates that flank the mountains are exposed in roadcuts.

About 14 miles southwest of Baker, the highway descends the southwest slope of the Soda Mountains into Cronese Valley which is occupied by Cronese Dry Lake. Cat Mountain borders the lake on the west (Map 11); Cave Mountain is south of the road. Both are underlain mainly by Mesozoic (?) granitic rock. Cat Mountain derives its name from the large, cat-shaped hanging dune which lies on its east slope. Cronese Valley is another sink of the Mojave River, whose flowage commonly extends northward and around the east side of Cave Mountain.

Afton garage, 25 miles southwest of Baker, is near the ancient shoreline of Manix Lake which in Pleistocene time covered an area of at least 200 square miles (Buwalda, 1914). For several miles southwest of here, the dissected and only slightly deformed beds of Manix Lake are exposed along the highway. The lake was fed by the Mojave River and had an outlet through Afton Canyon to the south of Cave Mountain. It occupied a basin in which fanglomerates previously had been deposited. As the basin became filled with sediment and the outlet was downcut, the lake drained and its beds were eroded. The Manix Lake beds consist of clay and sandstone strata and are about 75 feet in maximum observed thickness. Immediately west of the garage a side road extends southeastward (left) along a well-preserved gravel bar that marks the former position of the lake shore.

From a point 2 miles west of Manix to the Barstow area, the Calico Mountains (Erwin, H. D., and Gardner, D. L., 1940) dominate the landscape north of the highway. These mountains derive their name from the brilliantly colored calico-patterned volcanic rocks that are extensively exposed on their slopes. They are known historically for the bonanza silver deposits that were most actively mined in the period 1882-96, and for the colemanite deposits which during much of the period 1884-1907 were the world's principal source of borate minerals.

In general the Calico Mountains consist of Tertiary volcanic and sedimentary rocks that rest upon a basement of Paleozoic sedimentary rocks and Mesozoic intrusive rocks. The layered Tertiary rocks are 10,000 or more feet thick. The lower part of this section is unfossiliferous, but the upper one-third contains vertebrate fossils of early upper Miocene age. The entire section is intruded by numerous Pliocene (?) volcanic rocks that range in composition from calcic andesite to rhyolite. These plugs, which underlie about half the area of the Calico Mountains, range from a few feet to 3 miles in diameter. The Calico Mountains are structurally very complex, but in general they form a southeastward extension of the northeast limb of the Barstow syncline, a major structural feature that lies mainly north of Barstow. The rocks are intimately faulted and have been elevated along a major frontal fault zone.

Part of the Tertiary section of the Calico Mountains extends into the low hills north of the highway and about 2 miles east of the Calico Mountains. These Tertiary strata have yielded middle to upper Miocene vertebrate fossils. The small prominent hill about 1 mile west of Toomey and only a few yards north of the highway is a north-facing fault scarp that marks an eastward extension of a branch of the frontal fault zone that borders the Calico Mountains on the south. The hill is composed of siltstone that apparently was deposited by the Mojave River, as the only nearby occurrence of such material is in the present river channel. The frontal fault extends southeastward across the Mojave River and into the Ord Mountains, and creates a water barrier beneath the Mojave River channel.

The Newberry and Ord Mountains (Gardner, 1940), which lie south of the Mojave River and approximately opposite the Calico Mountains, are underlain mostly by pre-Tertiary crystalline rocks.

About 3 miles west of Yermo (Map 12), the highway crosses low hills underlain by Tertiary tuffaceous beds interlayered with various sedimentary rocks that include the resistant limestone exposed near the highway. They are intruded by sills of diabase and felsite. The hills that adjoin these hills to the northwest are bordered on the southwest by the Waterman fault, a major structural feature that trends northwest. Continue on U.S. Highway 91 to Barstow.

Barstow to San Bernardino

The country between Barstow and Victorville shows isolated hills and groups of hills which consist of pre-Cretaceous crystalline rocks that project above a gently rolling alluviated surface. In general the road follows a broad arc of the Mojave River. Of particular interest in this area are the broad topographic domes that reflect a Quaternary arching of Pleistocene alluvium. The area is traversed by several northwest-trending faults, but fault scarps generally are not well developed near the highway.

The only Tertiary volcanic rocks seen from this segment of the route are dacite plugs that form the prominent red knobs in the Barstow area. The broad, relatively smooth surface south of Barstow is underlain by slightly deformed Pleistocene alluvium. The low hills northwest of Barstow contain gneissic hornblende diorite intrusive into limestone, quartzite, and mica schist of the Carboniferous Oro Grande series.

About 2 miles from Barstow the highway crosses the trace of a fault whose northwestward extension is shown by the southwest-facing escarpment of the Hinkley Hills on the north side of the Mojave River. This fault acts as a barrier to subsurface waters of the Mojave River channel and forces the water table upward at the fault plane.

The Pleistocene alluvium, southeast of the highway between Barstow and Lenwood, underlies a broad topographic rise whose summit marks the axis of a broad, gentle anticline that trends northwestward toward Lenwood. The Iron Mountains lie west of the river opposite the Lenwood area. The most prominent peaks of these mountains consist of black hornblende diorite (Mesozoic). The highly colored surface that slopes toward the river is a dissected and exhumed pediment cut during middle Tertiary time. This surface is underlain by the Hodge volcanic series (Paleozoic ?), which consists of rhyolite and dacite flows and tuffs.

From a point on the highway about 4 miles southwest of Hodge can be seen the profile of a gentle rise in Pleistocene alluvium west of the Iron Mountains. This rise is the surface expression of a broad fold in the alluvium which has been produced by movement along the Helendale fault in the bedrock beneath the alluvium. This fault extends southeastward into the San Bernardino Mountains a distance of nearly 50 miles, and is the principal fault in the Barstow-Victorville area. Its trace is crossed by the highway at a point about 6 miles southwest of Hodge. The Helendale fault is expressed topographically in the escarpment that forms the northeast face of the Silver Mountains, to the southeast of the highway. The Silver Mountains consist almost entirely of metavolcanic rocks of the Sidewinder series (Triassic ?).

The surface flow of the Mojave River generally disappears midway between Helendale and Oro Grande and does not normally reappear until it flows over bedrock in the floor of Afton Canyon about 50 miles to the northeast. It has been said that the Mojave River has one of the most porous channels in the United States. Even from where the river emerges from the San Bernardino Mountains, it most commonly flows beneath the surface until it rises over bedrock near Victorville.

A prominent white scar high on the slope of the Silver Mountains 3½ miles east of Bryman marks the location of hydrothermal alteration zones in volcanic rocks of the Sidewinder series. Dacite has been altered along fractures to a very fine-grained mixture of sericite-quartz which is mined and used as a nonmetallic filler.

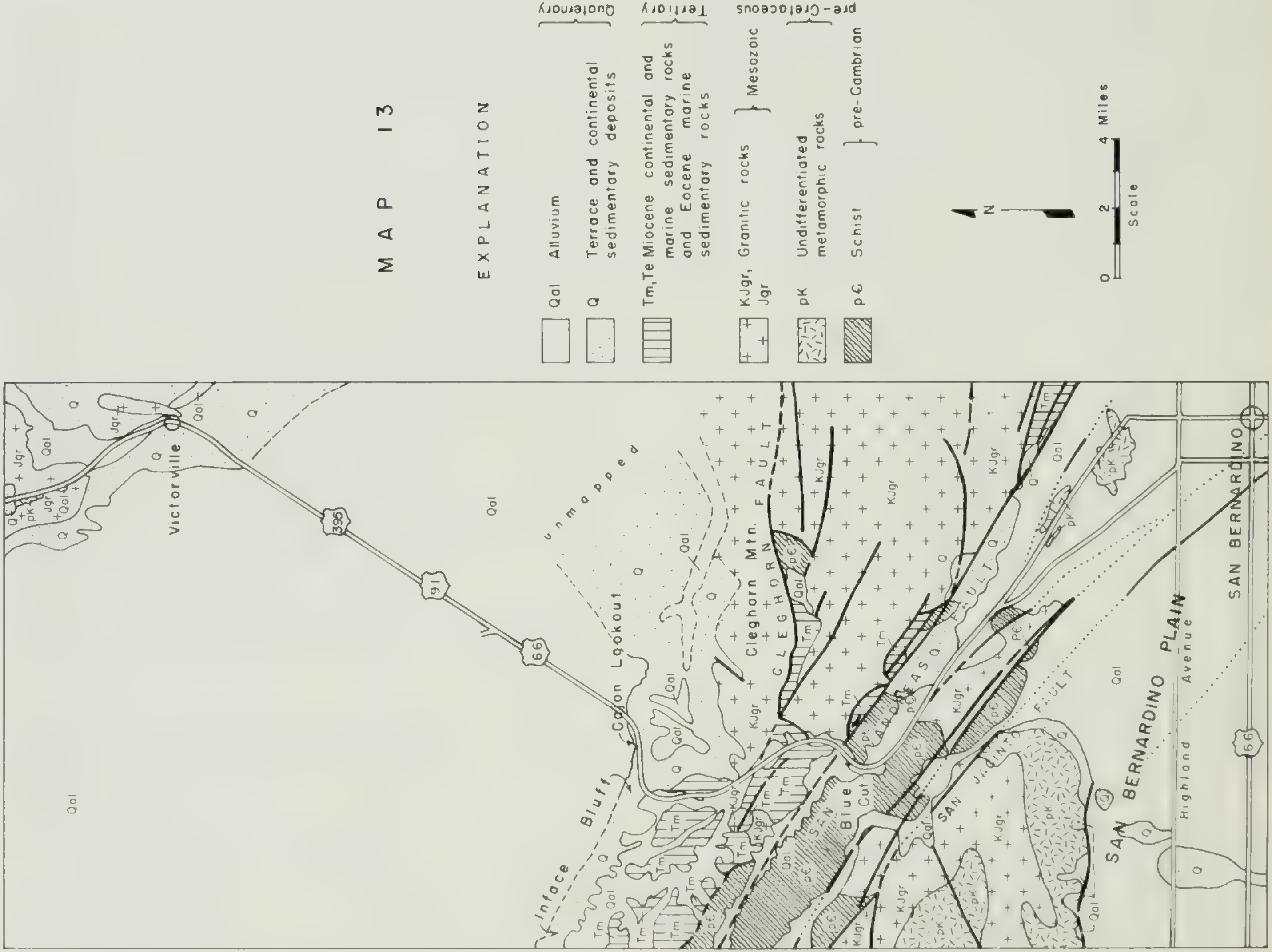
About 3 miles south of the white patch, limestone is extracted from numerous quarries on the flanks of Silver and Quartzite Mountains and transported to kilns at Oro Grande and Victorville, where it is used in the manufacture of cement. The limestone is part of the Oro Grande series (Carboniferous) whose type locality is at Quartzite Mountain. The series has a maximum measured thickness of 9,670 feet; it consists of white crystalline limestone, fine-grained quartzite, and mica schist. Twelve miles to the east the series is unconformably overlain by the Fairview Valley formation (Permian), which consists of 6,000 feet of metamorphosed siltstone, limestone, sandstone, and limestone conglomerate, and supplies limestone for the cement plant near Victorville.

Alluvial deposits of upper Pleistocene age are prominently exposed along the west side of the Mojave River between Helendale and Victorville. Quartz monzonite of probable middle Mesozoic age is exposed east of the highway, from Oro Grande to the bridge 2 miles south of Oro Grande. The quartz monzonite on the south slope of Quartzite Mountain underlies a dissected pediment which has been entrenched by the Mojave River at the Lower Narrows near the bridge. The Upper Narrows has been cut through quartz monzonite at Victorville.

From Victorville (Map 13) the route of travel extends southwestward on U.S. Highway 91 across a nearly level, north-sloping surface which is underlain by Quaternary fanglomerate and alluvium. This is essentially the surface of a very large alluvial fan that once extended continuously to its source in the San Bernardino and San Gabriel Mountains. Most of the streams that deposited the fan, however, have been captured by the headward erosion of Cajon Creek, which flows southward between the San Bernardino Mountains on the east (left) and the San Gabriel Mountains on the west (right). The fan is separated from these mountain fronts by west and east branches of Cajon Creek; it contains the channels of ancient streams that once headed in the mountains. These channels are most prominent on the higher slopes of the fan and are beheaded on the south-facing Inface Bluffs that extend both east and west from Cajon Summit.

Cajon Summit (elev. 4,301) is on the rim of the Mojave Desert and at the south boundary of the vast area of interior drainage of which the Mojave Desert is a part. From the vicinity of the Summit Lookout Station the observer can look to the north where the desert floor slopes gently away from the rim of the bluff and merges with pediments and alluvial fans of various mountain ranges. Cajon amphitheater, which occupies the broad, low, brush-covered area south of the desert rim, is occupied by tributaries of Cajon Creek.

The surface to the south (right) of the railroad summit, southeast of the lookout station, is the westernmost extension of Horsethief Canyon, a wide valley that once extended westward to the San Gabriel Mountains and was occupied by a western tributary of the Mojave River. After the valley was cut, its floor was partly filled with



MAP 13

EXPLANATION
Qal Alluvium
Q Terrace and continental sedimentary deposits
Quaternary
Tm, Te Miocene continental and marine sedimentary rocks and Eocene marine sedimentary rocks
Tertiary
KJgr, Jgr Granitic rocks
Mesozoic
pK Undifferentiated metamorphic rocks
p€ Schist
pre-Cambrian
pre-Cretaceous
N
0 2 4 Miles
Scale
Victorville
395
91
66
unmapped
Cajon Lookout
Inface Bluff
Cleghorn Mtn.
CLEGHORN FAULT
SAN ANDREAS FAULT
SAN JACINTO FAULT
Blue Cut
SAN BERNARDINO PLAIN
SAN BERNARDINO
Highland Avenue
Qal
Q
Jgr
KJgr
pK
Tm
p€

alluvial debris and it was subsequently truncated by the headward erosion of Cajon Creek.

The brown Quaternary alluvium that caps the Inface Bluffs is composed almost entirely of angular fragments of Pelona schist derived from the San Gabriel Mountains. The debris was deposited before the Cajon amphitheater was excavated, for the amphitheater lies between the material and its sources.

Magnificent exposures of the Inface gravel of upper Pleistocene age exist in highway cuts in the bluff below the summit. Here the gravel is about 800 feet in exposed thickness and dips 25° to 30° N.

The Horsethief formation (Pleistocene), which is at least 1,200 feet thick and consists of nonmarine gravel and clay, lies unconformably beneath the Inface gravel. In some places this formation rests upon granite and in other places upon older sandstone. It is exposed in a strip half a mile to 2 miles wide in the northern part of Cajon amphitheater. It underlies all of the low area south of the summit between the highway and Cleghorn Mountain.

The Cajon (upper Miocene) formation underlies several square miles in the southern part of the Cajon amphitheater and occupies a narrow belt adjacent to the San Andreas fault. It consists of about 9,500 feet of nonmarine strata, chiefly arkosic sandstone and conglomerate, but includes beds of shale and algal limestone. It is most easily distinguished by a pale buff color and by its barren and picturesque outcrops. Exposures of upturned sandstone of the Cajon formation lie on both sides of the highway near Cajon Creek. Lower Miocene marine sandstone and shale of the Vaqueros formation are locally exposed in the area of Cajon Junction, and patches of Paleocene conglomerate, sandstone, and siltstone of the Martinez (?) formation occur near the highway northeast of Blue Cut.

From Cajon Summit southward to the San Bernardino plain the route of travel lies within the San Andreas fault zone, which, in general, occupies the belt of low relief that separates the San Bernardino and San Gabriel Mountains. This belt is marked by a series of low, parallel, even-crested ridges that slope gently southeastward. These ridges are underlain by Pelona schist and nonmarine sedimentary rocks of the upper Miocene Cajon formation.

South of Cajon Junction pre-Mesozoic gneisses and metasedimentary rocks underlie the Martinez (?) formation. Roadcuts along the east side of the highway successively show strata of the Cajon formation, a Quaternary gravel, Martinez (?) strata, and granodiorite. The Martinez (?) formation dips north and is apparently in depositional contact with the granodiorite.

About a third of a mile southwest of the granodiorite exposure the road crosses the main break of San Andreas fault, which here is marked by the marshy area left of the highway. Blue Cut, the high roadcut just beyond the marshy area, contains highly shattered and brecciated Pelona schist. The sharp bend in Cajon Creek at Blue Cut is believed to be the effect of about a mile of horizontal displacement along the San Andreas fault (Noble, 1933). Numerous faults parallel to the San Andreas cut the schist, and narrow bands of crushed greenstone and gneiss are faulted into the steeply dipping schist.

Southeast of Blue Cut the road parallels Cajon Creek. The San Andreas fault lies northeast of the highway and trends southeastward along the base of the San Bernardino Mountains.

Scarps of the San Andreas fault in Quaternary terrace deposits can be observed in side roads east of the highway below Blue Cut Tower. From Devore one can follow several routes to Los Angeles, all of which are parallel to the south flank of the San Gabriel Mountains and traverse the extensive piedmont fans extending out from the mountains.

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

GEOLOGIC GUIDE NO. 2
VENTURA BASIN

1954

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO

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San Francisco · Bulletin 170 · September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

GEOLOGIC GUIDE NO. 2

VENTURA BASIN

By CHARLES W. JENNINGS *and* BENNIE W. TROXEL

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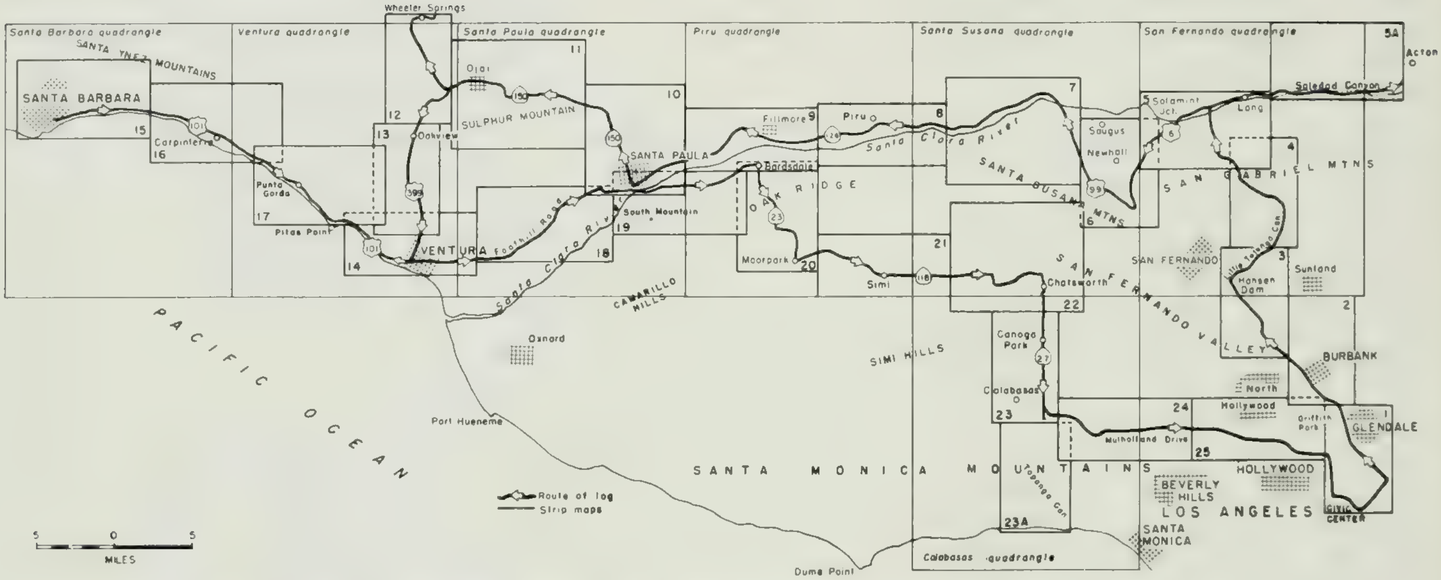

Fig. 1. Index to strip maps for Geologic Guide Through the Ventura Basin, Southern California

GEOLOGIC GUIDE THROUGH THE VENTURA BASIN AND ADJACENT AREAS, SOUTHERN CALIFORNIA

By Charles W. Jennings* and Bennie W. Troxel**

INTRODUCTION

Between Los Angeles and Santa Barbara a great variety of geologic features vividly illustrates the stratigraphic and structural characteristics of the Transverse Range province of southern California. The Ventura basin, a particularly complex unit in the geologic framework of this province, is an elongate, east-trending trough in which a thick section of sedimentary rocks has accumulated throughout most of Tertiary time. Like most of the other units in the province, this basin lies athwart the characteristic northwest structural trend of the Coast Ranges of California.

The area is underlain almost entirely by highly folded sedimentary rocks, of Cretaceous to Recent age, that are interbedded locally with volcanic rocks. The Cenozoic geologic record is unusually complete, and, within a 3-mile radius of a single site in the basin (near Fillmore), one can see rocks representing at least a part of every epoch since the beginning of Eocene time. A 20,000 foot section of continuous Pliocene and Pleistocene marine strata near Santa Paula is believed to be the thickest in California, and one of the thickest in the world.

The recency of folding is one of the most striking geologic features in the Ventura basin. Extensive thrust faults and numerous folds exhibit the influence of compression as the major factor in the development of the structures. Such structural features can be viewed at many places in the Ventura basin.

The route of travel for this field trip is more than 200 miles long, and was chosen to provide the best possible examples for observation and detailed examination of many outstanding geological features. This route is illustrated on 25 adjoining strip maps (plus 2 maps for side trips) which are annotated in order to emphasize significant details. The maps are accompanied by a text in which the more prominent features are described and discussed. Although the route is best regarded as a continuous trip, its description has been organized so that any part or parts can be used independently of the remainder by those who cannot complete the entire trip at one time.

The different areas traversed by the route of this trip have been described under the following headings:

- Los Angeles area
- San Fernando Valley
- San Gabriel Mountains
- Soledad basin and eastern Ventura basin
- Santa Paula -- Ojai Valley
- Wheeler Hot Springs -- Ventura
- Santa Barbara and vicinity
- Western Santa Clara River Valley
- Bardsdale -- Simi Valley -- Santa Susana Pass
- Santa Monica Mountains -- Cahuenga Pass

In the itinerary of the log stops are indicated where one can view geologic features and review the nature of the agents that produced them. For example, at Stop 14 on the bank of Santa Paula Creek, small-scale structural features in Pliocene sediments illustrate deposition in deep water by turbidity currents. A site in the Santa Monica Mountains where rhythmic bedding in siliceous shales is displayed possibly indicates depositional control by climatic oscillations.

Many structural features--including thrust faults, innumerable folds, and unconformities--also can be viewed. In the San Gabriel Mountains a ‘basement’ complex of gneiss has been folded and thrust over Pliocene sandstones. In the same region, crushed and sheared rocks along the San Gabriel fault, one of California’s large strike-slip faults and part of the system that includes the San Andreas fault, can be examined in detail. Between Santa Paula and Ojai are excellent views of the San Cayetano and Oakridge thrusts, which border the Santa Clara Valley syncline on the north and south, respectively. Deformation has been going on intermittently throughout the region during the Tertiary and Quaternary periods, so that many unconformities and marked lateral changes in lithology characterize the sedimentary section. Within distances of a few miles, facies changes from coarse sandstone and conglomerate to shale are well displayed in sections several thousand feet thick. Deformation has continued to the present time, so that at many places the modern topography is being modified by diastrophism. Near Carpinteria, for example, a thrust fault has brought Miocene rocks up over terrace deposits of late Pleistocene age.

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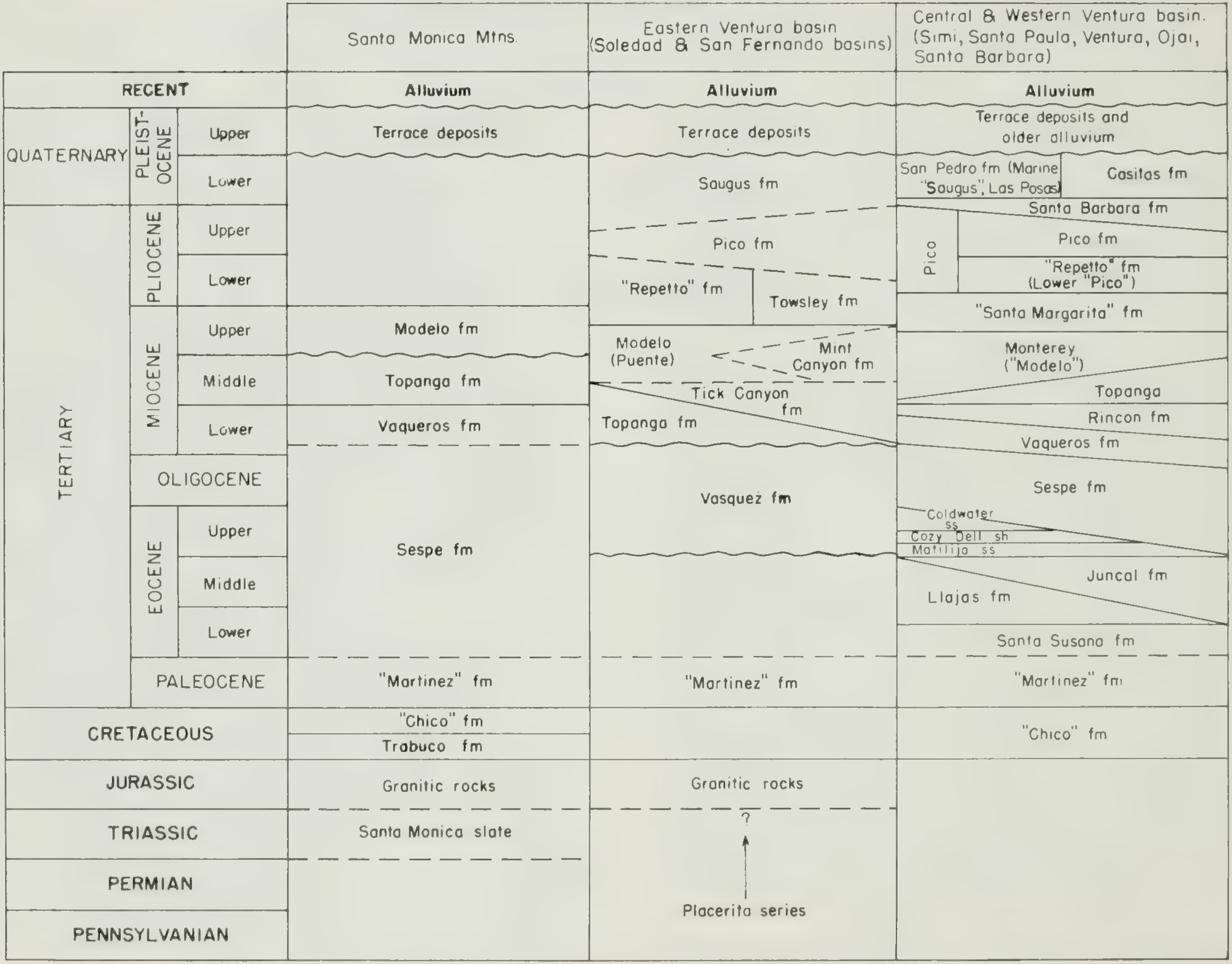


Fig. 2. Geologic formations in the Ventura basin and adjacent areas

DESCRIPTION OF GEOLOGIC FORMATIONS

Formation	Map symbol	Description and remarks
Alluvium	Qal	Unconsolidated sand, gravel, and silt. Extensive in lowland areas and in stream channels.
Terrace deposits	Qt	Stream-laid gravels along valleys of the main streams and along coast. Locally tilted. Some of marine origin.
Casitas	Qc	Nonmarine gravels in Carpinteria area (Upson, 1951).
San Pedro	Qs	Marine sediments along Santa Clara River Valley. Included in 'marine Saugus' (Los Posas) formation by some investigators. Type locality in Palos Verdes Hills.
Santa Barbara	Qsb	Marine marl, sand, and shale. Found along coast between Santa Barbara and Ventura and in Santa Clara Valley. Type locality at Packard's Hill (Grant and Gale, 1931).
Saugus	Ps	Nonmarine deposits; widespread, generally in eastern half of Ventura basin. Originally included in Fernando formation of Hershey (1902); defined as formation by Kew (1923). Nonmarine in type locality, but includes some marine (lacustrine) and brackish water deposits to west. Restricted to Pleistocene by Woodring (1932). Grades upward into San Pedro formation (Eaton 1928).
Pico	Pp	Marine siltstone, shale, and sandstone; local conglomerate members. Widespread in Ventura basin except for Santa Barbara area. Included in Fernando group by Kew (1923). Restricted by Woodring (1932) to upper and middle Pliocene and later (1937) to upper Pliocene. Includes upper and middle Pliocene on accompanying maps.
Repetto	Pr	Marine sediments. Type locality in Los Angeles basin. Name used by some investigators in Ventura basin.
Towsley	Pt	Marine sediments. Type locality near Pico anticline west of Newhall (see Winterer, this volume). Regarded as equivalent to Santa Margarita by some investigators.
Castaic	Mc	Marine sandstone, shale, and conglomerate (see Crowell, this volume).
Mint Canyon	Mmc	Nonmarine sediments. Believed to interfinger with marine Miocene beds in the subsurface near Newhall. Generally east of San Gabriel fault.
Tick Canyon	Mtc	Nonmarine. Ventura basin east of San Gabriel fault.
Santa Margarita	Msm	Marine. Mostly upper Miocene siltstone and shale in Ventura basin. Type locality in San Luis Obispo County.
Monterey (Modelo)	Mm	Marine diatomaceous shale, sandstone, and chert. Widespread. Modelo in Santa Monica Mountains unconformably overlies Topanga (M. Miocene).
Puente	Mp	Marine beds. Type locality in Los Angeles basin. Sometimes called Modelo in eastern Santa Monica Mountains.
Topanga	Mt Mtv	Marine sandstone and conglomerate with volcanic intrusive and extrusive rocks. Type locality in Santa Monica Mountains.
Rincon shale	Mr	Marine mudstone and shale. Type locality Los Sauces Creek, Rincon Mountain.
Vaqueros	Mv	Marine sandstone. Generally accepted as oldest Miocene strata in southern California. Type locality in Monterey County.

Formation	Map symbol	Description and remarks
Sespe	Φs	Generally considered nonmarine, but may not be in its entirety. Characteristically red, but also green, white, and gray sandstone, siltstone, shale, and conglomerate. Grades into overlying lower Miocene marine beds and underlying upper Eocene strata.
Vasquez	Φv Φvv	Nonmarine beds, containing interlayered intrusive and extrusive volcanic rocks. Regarded as equivalent to Sespe formation by some investigators. Extensive in Ventura basin northeast of San Gabriel fault.
Coldwater sandstone	Ecw	Marine white sandstone, with local red and green shale. Type locality in Santa Ynez Mountains. Nonmarine in part.
Cozy Dell shale	Ecd	Marine dark gray sandy shale. Type locality in Santa Ynez Mountains.
Matilija sandstone	Emj	Marine buff sandstone. Type locality in Santa Ynez Mountains.
Juncal	Ej	Marine, dark gray shale, sandstone, and thin lenses of limestone. Type locality Santa Ynez Mountains.
Llajas	El	Marine beds. Type locality Simi Valley.
Santa Susana	Es	Marine basal conglomerate and shale. Type locality Simi Valley.
Martinez	Epm	Marine sandstone and shale. Commonly not differentiated from underlying Upper Cretaceous strata in the Santa Monica Mountains and from overlying Eocene strata elsewhere.
'Chico'	Kc	Marine sandstone, shale, and local conglomerate. Occurs in Simi Hills, Santa Monica Mountains and Santa Ynez Mountains.
Trabuco	Kt	Nonmarine clayey red conglomerate. Occurs in Santa Monica Mountains. Type locality Santa Ana Mountains.
Granitic rocks		Granitic intrusive rocks in the San Gabriel and Santa Monica Mountains. Ranges from granite through norite. Highly weathered locally in Santa Monica Mountains. Dating indefinite.
Santa Monica	Trsm	Black shale and graywacke dynamothermally metamorphosed to slate and schist.
Placerita series		Metasediments and meta-intrusive rocks in the San Gabriel Mountains. Dating indefinite, but may be Paleozoic.

The formation of the Ventura basin probably was initiated in Paleocene time. At that time the western half of southern California was affected by a large downwarp that permitted invasion by the sea and attendant deposition of marine sediments over a vast area. By the end of Miocene time the San Gabriel, Santa Monica, Santa Ynez, and Topatopa Mountains were developed, splitting the single basin into several smaller ones, including the Los Angeles, Ventura, and Santa Maria basins. Faunal evidence indicates that by early Pliocene time, the central part of the Ventura basin was covered by a sea 5,000 feet deep. The basin continued to sink even until Recent time, although at a reduced rate, until sedimentation exceeded the rate of subsidence and it became filled.

The problems of stratigraphic interpretation and nomenclature in this region are among the most difficult in the world. The selection of the formational names that are shown on the following maps posed a formidable problem, and no doubt those used will not be fully acceptable to all local investigators. In recent years the introduction of stage names for divisions of the various Tertiary epochs has been invaluable for standardizing local correlations, and in the future, when they have become better defined and more widely accepted, these names should be of further aid. For the purposes of this roadlog, it was deemed advisable to refrain from the use of stage names, and instead to explain in the columnar section (fig. 2) the variances in uses of the formational names that appear on the strip maps and in the text of the road log.

The primary economic wealth of the Ventura basin, aside from agriculture, is represented by petroleum. Figure 3 presents geologic and production data for the oil fields in this basin.

Completion of this geologic road log was made possible by the generous assistance of many people, whose contributions are gratefully acknowledged. The route of the trip was suggested by John C. Crowell, and his assistance with the preliminary field work and his criticism of the maps and manuscript were especially helpful. Among those who offered constructive advice and who conducted the authors through several of the field areas are: Cordell Durrell (Santa Monica Mountains); D.V. Higgs (San Gabriel Mountains); E.L. Winterer (eastern Ventura basin); L.E. Redwine and T.L. Bailey (Santa Barbara and Ventura areas); and R.H. Paschall, Spencer F. Fine, H.H. Neel, and J.F. Curran (Santa Clara River Valley and Ojai Valley areas). The work was frequently discussed with L.A. Wright and R.H. Jahns, who also read and edited the complete manuscript.

Additional information and revisions of previously published geologic maps have been provided by T.L. Bailey, R.H. Jahns, W.R. Muehlberger, R.P. Sharp, Cordell Durrell, E.L. Winterer, A.O. Woodford, and L.E. Redwine. In addition, theses from nearby universities have yielded much useful information.

Figure 3. OIL FIELDS IN THE VENTURA BASIN

(Includes Ventura district, Santa Clara Valley district, and part of Santa Barbara district)

Name	Discovery date	Age of producing formations	Structure	Production (thousands of barrels)		Approximate location (Map no.)
				1952	Total to 1-1-53	
SANTA BARBARA DISTRICT						
Santa Barbara	May 1929	Miocene	faulted homocline	7	3,652	
Summerland	1887	Pliocene, Pleistocene	faulted anticline	5	3,194	15
VENTURA DISTRICT						
Rincon	Dec. 1927	Pliocene	faulted anticline	2,289	38,199	17
Padre Canyon	1931	Pliocene	faulted anticline	759	7,865	17
San Miguelito	Nov. 1931	Pliocene	faulted anticline	4,250	31,922	17,14
Ventura	1916	Pliocene	faulted anticline	27,421	448,239	13,14
SANTA CLARA VALLEY DISTRICT						
Aliso Canyon	Oct. 1938	Pliocene, Miocene Eocene	complex	2,428	16,124	East of 22
Bardsdale	1891	Oligocene, Eocene	asymmetrical domes	646	5,289	20
Castaic Junction	Jan. 1950	Miocene	faulted anticline	528	834	7
Conejo	1892	Miocene	monoclinal	1	103	--
Del Valle	Sept. 1940	Pliocene, Miocene	faulted anticline	1,229	15,965	7
Honor Rancho	Aug. 1950	Miocene	anticline	2,251	2,595	North of 7
Las Llajas	1945	Eocene	anticline	3	14	--
Montalvo-west	Apr. 1947	Pliocene, Oligocene		308	1,295	--
Newhall group				61	6,983	
Elsmere Canyon	1889	Pliocene, Eocene				6
Pico Canyon	1875	Miocene	anticline			7
Towsley Canyon	--	Miocene	anticline			7
Tunnel	--	Pliocene	faulted homocline			6
Whitney Canyon	1893	Pliocene	homocline			
Wiley Canyon	1887	Miocene	anticline			6
Newhall-Potrero	Mar. 1937	Miocene	faulted anticline	2,851	28,597	7
Oak Canyon	Feb. 1941	Miocene	faulted anticline	507	5,913	North of 7
Oak Ridge	Aug. 1952	Miocene	anticline	188	188	8
Oat Mountain	May 1946	Eocene		19	36	North of 22
Ojai Group	1885	Miocene, Oligocene, Eocene	complex; thrust faulting	195	4,182	11
Lion Mountain	1935	Oligocene	anticline	12	130	11
Sisar-Silverthread	1885	Pliocene-Miocene		38	3,186	10
Sulphur Mountain	1927		faulted homocline	--	96	
Sulphur Mountain-North	1912	Miocene	anticline	144	666	11
Oxnard	June 1937	Miocene		624	4,379	South of 18
Piru Group	1887-1951	Pliocene, Miocene	anticlinal	278	7,855	North of 8
Placerita		Pliocene		3,458	18,379	5,6
Juanita area	1949	Pliocene		1,887	13,655	5,6
Old area	1920	Pleistocene		1,571	4,724	5,6
Ramona	Nov. 1943	Miocene	homoclinal	1,287	10,663	7
Santa Paula Group				244	3,335	10
Adams Canyon						10
Timber Canyon	1950	Pliocene-Miocene		234	1,195	10
Wheeler Canyon				3	--	North of 18
Shiells Canyon	1911	Oligocene	anticline		15,090	9
Simi	1912	Oligocene, Eocene	faulted anticline		2,558	21
South Mountain	1916	Oligocene	faulted anticline	2,858	39,998	10, 19
Tapo South	Mar. 1950	Miocene			1	
Torrey Canyon	1896	Oligocene	anticline	246	6,223	[illegible]
Weldon Canyon	June 1951	Pliocene		38	61	6
West Mountain	Feb. 1945	Oligocene	anticline	148	1,381	19

LOS ANGELES AREA

MAP 1

The civic center of Los Angeles lies in low hills between the Santa Monica Mountains on the northwest and the Los Angeles Plain to the south. The hills consist of south-dipping Miocene marine sandstone and siliceous shale overlain by Pliocene marine sandstone, siltstone, and shale. The Tertiary units are flanked on the south by considerable thicknesses of Quaternary alluvium. Other hills that border the basin contain similar sedimentary rocks and afford surface outcrops of rocks that are encountered in wells drilled in the basin. (A description and geological map of Los Angeles basin is included in the Geologic guide for the Los Angeles Basin, southern California, Guide number 3, this bulletin.)

Los Angeles City oil field

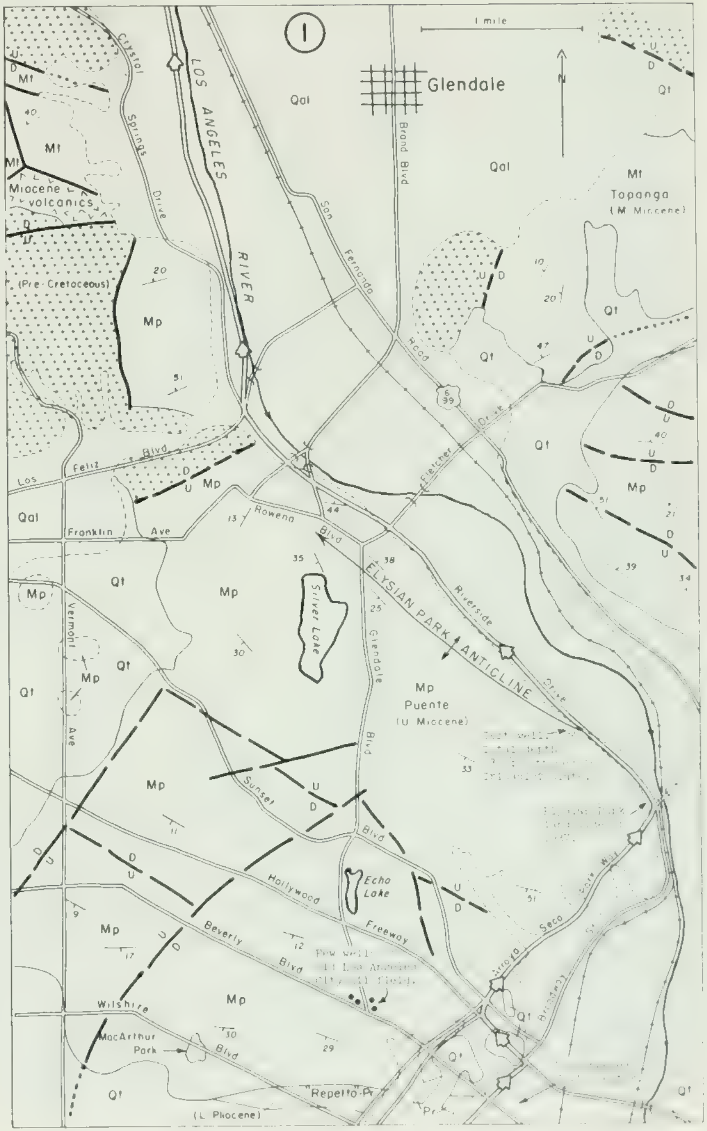
The old Los Angeles City oil field, which is crossed near the intersection of Figueroa Street and Sunset Boulevard, is now nearly abandoned. Approximately a thousand wells were drilled up to 1907, when city restrictions curtailed further drilling. The field lies along a narrow zone of minor faulting and sharp folding in Tertiary rocks on the south limb of the Elysian Park anticline, and extends 4 miles to the west. Production is obtained from an upper sandstone unit of the Puente formation (upper Miocene).

Elysian Park anticline

The Elysian Park anticline, a major northwest-trending fold, has pronounced topographic expression and can be traced for 6 miles on the basis of surface data. It forms an elliptical dome that plunges distinctly at both ends. The axis of the fold can be readily observed where it crosses Glendale Boulevard and it also can be seen at Pasadena Avenue. Rapid downcutting by the Los Angeles River has kept pace with the upfolding of the Elysian Park anticline, and thus the river is antecedent where it crosses the axis of the fold.

Elysian Park landslide

On Riverside Drive, a few hundred feet northwest of the Figueroa Street tunnels, is the site of the Elysian Park landslide of November 1937. Evidence of downslope creep of part of the hill was first noticed on October 28, 1937, when cracks appeared in the asphalt of Elysian Park Drive, on the hillside above Riverside Drive. Gradual movement, increasing daily, culminated in a sudden slide of more than a million tons of rock and soil on November 26, 1937. Both Elysian Park Drive and Riverside Drive had been closed to traffic prior to the landslide,



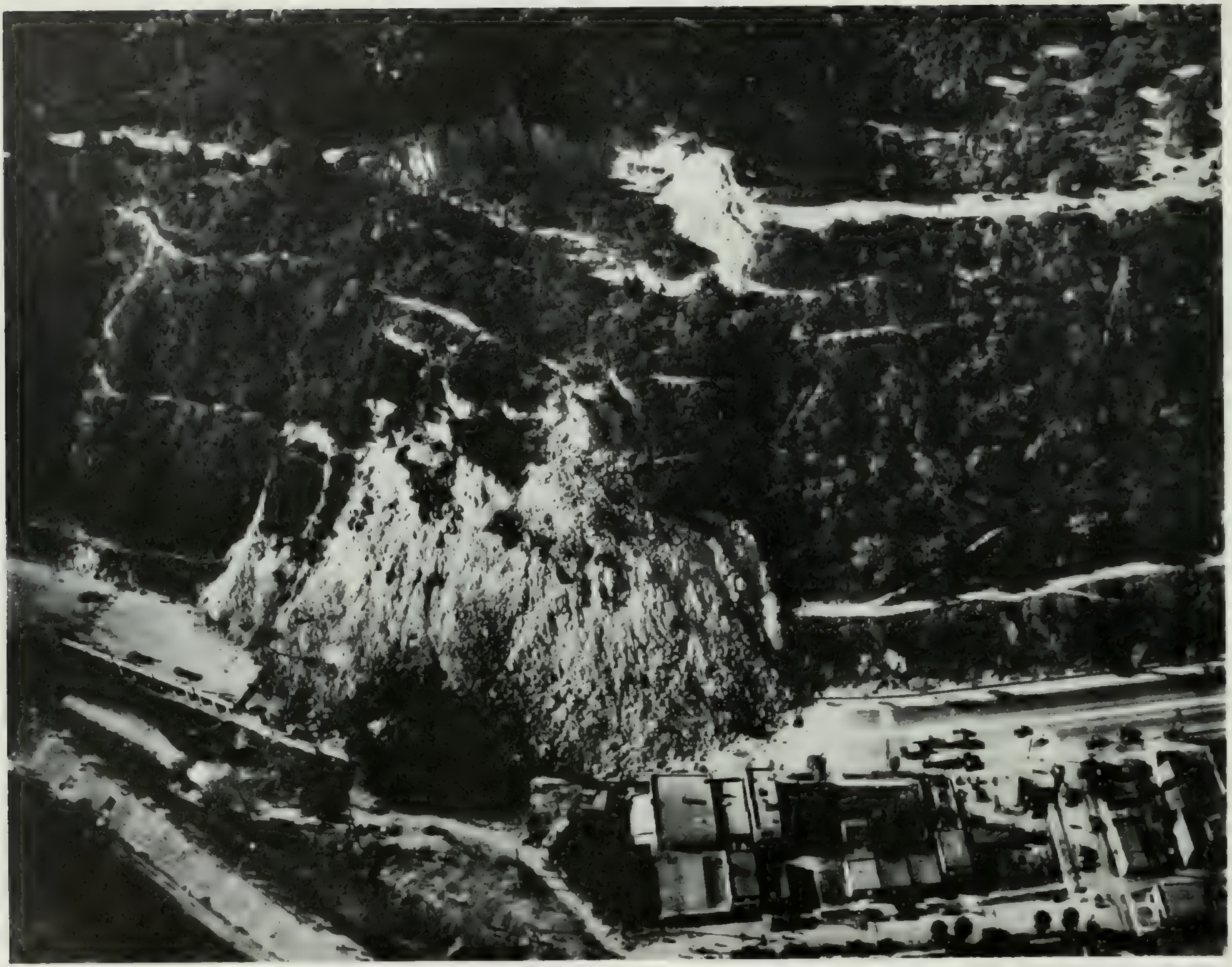


Fig. 4. Elysian Park landslide of November 1937. Riverside Drive in foreground is covered and the viaduct has collapsed beneath the weight of the broken rock. Elysian Park Drive area at the head of the slide subsided to form the steep cliffs. (Map 1.) Photo courtesy of Los Angeles Times.

and the public had been warned of impending danger.

Debris from the slide extended across Riverside Drive into the Los Angeles River. A large segment of Elysian Park Drive was removed by the slide, and 100 feet of the viaduct on Riverside Drive was destroyed. Water, natural gas, and power lines were sheared by the sudden movement. Nearly $500,000 was expended to repair damage caused by the slide. The viaduct was rebuilt, and was reopened to traffic a year after the sliding took place.

The steep escarpment along Riverside Drive was formed by the Los Angeles River. From just south of the point where Riverside Drive crosses the axis of the Elysian Park anticline, an exploratory oil well was slant-drilled under Elysian Park, and at a depth of 1,338 feet, it penetrated Santa Monica (?) slate of probable Triassic age.

Griffith Park

Griffith Park, at the eastern end of the Santa Monica Mountains, is underlain by Jurassic(?) granite, upper Miocene shale, and middle Miocene sedimentary and volcanic rocks. Granite in several stages of weathering, a thick section of steeply dipping Miocene shale, and basaltic dikes intrusive into granite and middle Miocene rocks are exposed along Crystal Springs Drive. From this road there is a good view of the Los Angeles River and the Repetto Hills to the east.

SAN FERNANDO VALLEY

MAP 2

San Fernando Valley is about 20 miles long and 3 to 9 miles wide; it is bordered by the Santa Monica Mountains on the south, the Simi Hills on the west, the Santa Susana and San Gabriel Mountains on the north, and the Verdugo Mountains on the east. The valley is drained by the Los Angeles River, which heads in the Simi Hills and flows along the north flank of the Santa Monica Mountains before swinging south around the eastern end of this range. The San Gabriel Mountains, which are about 2,500 feet higher than the Santa Monica Mountains, contribute more alluvium to the valley floor and consequently force the river to flow along the south margin of the valley.

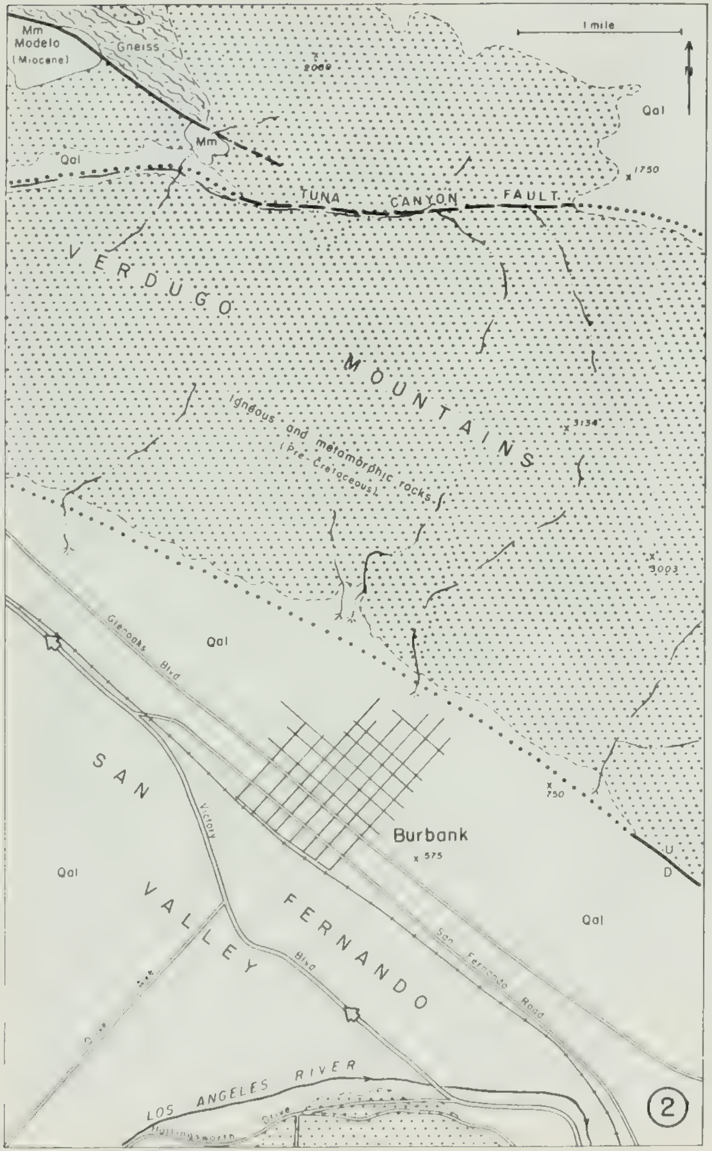
Geologic history

The Tertiary history of the San Fernando Valley area has been complex. During Eocene and Oligocene time marine and nonmarine deposition occurred near the northeastern part of the valley. Folding and faulting along the northern part of the valley was followed by accumulation of middle and upper Miocene sediments and middle Miocene volcanic rocks to considerable thicknesses in the valley area. Following further uplift, marine clastic sediments of Pliocene age were deposited along the northern edge of the present valley. These sedimentary rocks grade upward into nonmarine siltstone, sandstone, and conglomerate.

Pleistocene gravels are known to be 1,460 feet thick at the eastern end of the valley, and probably are thickest along the eastern and northern parts of the valley. Recent alluvium covers a large part of the present valley.

Verdugo Mountains

The Verdugo Mountains, consisting of metamorphic and igneous rocks, rise abruptly northeast of Burbank. The mountains are bounded on the south by a steep fault zone, and are separated from the main range of the San Gabriel Mountains to the north by other faults and by a narrow synclinal depression. Miocene volcanic rocks and Miocene and Pliocene sandstone and conglomerate are preserved in this depression.



MAP 3

Tujunga River Wash

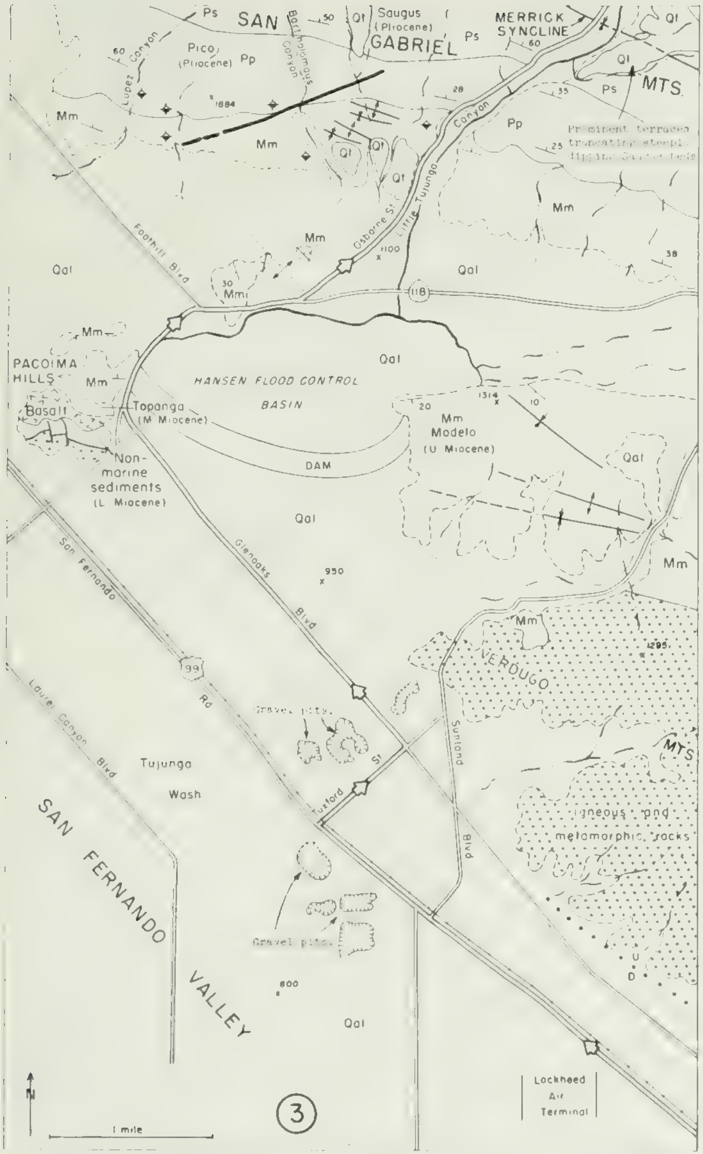
The pre-Cretaceous crystalline rocks at the northwest end of the Verdugo Mountains are overlain by folded Modelo (upper Miocene) sandstone and shale. Quaternary deposits in and near Tujunga Wash, which is crossed by Glenoaks Boulevard, have been the source of much of the sand, gravel, and crushed rock used by the construction industries in the Los Angeles metropolitan area. The deposits are part of a huge alluvial apron that extends southwestward from the base of the San Gabriel Mountains into San Fernando Valley. Coarse boulder gravels lie near the mountains, and fine-grained gravel and sand occur farther downstream to the southwest. The route of travel passes several of the huge pits in which the material is being excavated with power shovels and draglines. The large rock-crushing plants beside the pits reduce the boulders and cobbles to desired sizes, and the material is stored in high conical piles. This area, together with a similar one on the fan of the San Gabriel River to the east, yields more than half of the sand and gravel used in California.

Pacoima Hills

The Pacoima Hills lie at the western end of Hansen Dam. As shown on Map 3, granitic rocks of pre-Cretaceous age are exposed on the west side of the largest hill. Faulted against these 'basement' rocks is a belt of nonmarine beds (lower Miocene) from which vertebrate fossils have been recovered. These beds are overlain successively by basalt and by clastic sediments of the Topanga formation (middle Miocene). The northern end of the Pacoima Hills consists of Modelo (upper Miocene) sandstone and shale. The alluvium extending from the Pacoima Hills to the San Gabriel Mountains covers several complex structural features. Exploratory wells drilled for oil have penetrated an unexpectedly thin Tertiary section that overlies crystalline 'basement' rocks.

Hansen Dam

Hansen Dam, which extends across Tujunga Wash eastward from the Pacoima Hills, is a compacted earth-fill structure built by the U. S. Army Engineers as a means of flood control. The length of the dam along its crest is 9,050 feet, and its height at the spillway is approximately 100 feet. In 1938, several months before construction of the dam began, the most destructive flood on record poured down the ordinarily dry washes of Little Tujunga and Big Tujunga Canyons and caused property damage of more than $4\frac{1}{2}$ million dollars. In contrast, run-off



from heavy rains in 1941 and 1943 was controlled by the flood-control basin behind the dam and by the nearby Sepulveda flood control basin to the southwest, so that damage and public alarm were negligible.

SAN GABRIEL MOUNTAINS

San Gabriel foothills

From the valley floor the route of travel extends northward up Little Tujunga Canyon into the San Gabriel Mountains, which consist mostly of pre-Cretaceous granitic and metamorphic rocks, generally in fault contact with Cenozoic sediments on the flanks of the range. The low foothills at the mouth of Little Tujunga Canyon consist of north-dipping sedimentary rocks of upper Miocene, Pliocene, and Pleistocene age. They lie on the southwest limb of the Merrick syncline. Oil wells, one of which has produced a small amount of low gravity oil, have been drilled on smaller flexures in Bartholomaus Canyon and Lopez Canyon to the west.

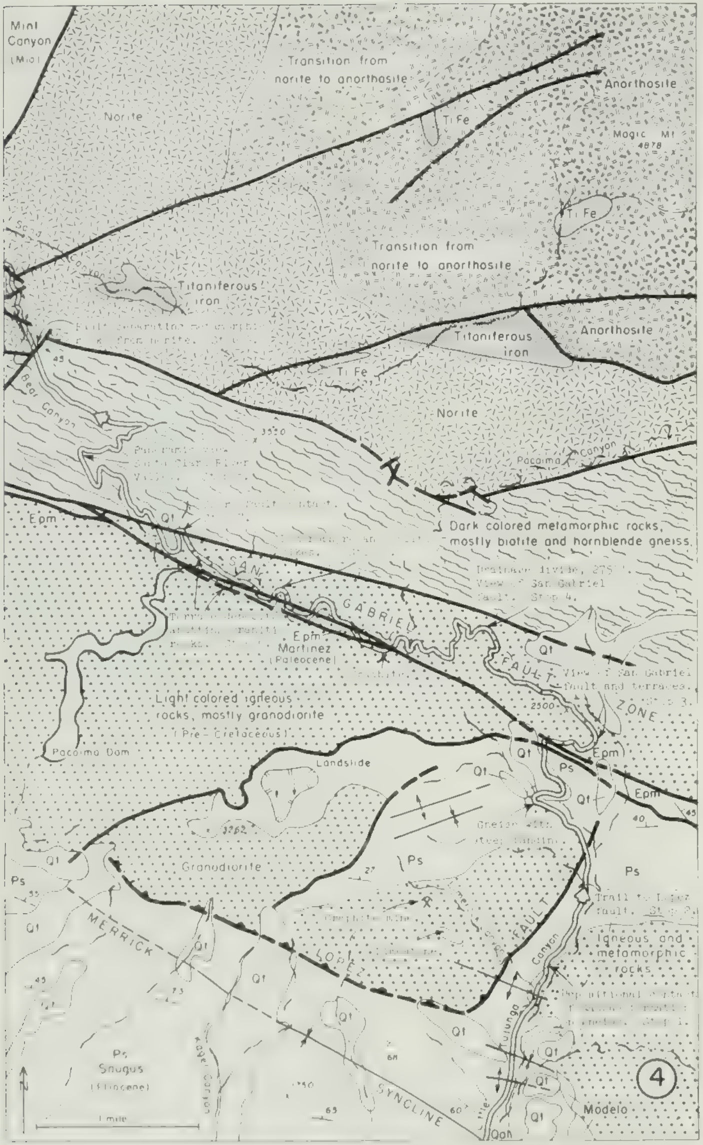
Approximately $1\frac{1}{2}$ miles upstream from the mouth of Little Tujunga Canyon, prominent stream terraces are displayed on the right (east) side of the road. This series of Pleistocene and Recent terraces truncates steeply dipping strata of the nonmarine Saugus (upper Pliocene) formation, and marks the positions of the canyon bottom as it existed prior to each rejuvenation of the stream. The pinkish brown and white sandstone and conglomerate exposed here in the roadcuts and canyon walls are typical of the Saugus formation, and show characteristic cross-stratification and graded bedding.

MAP 4

The axis of the Merrick syncline crosses the southern edge of Map 4, and the dips in the Saugus beds change abruptly from northeast to southwest on opposite sides of the fold. At Stop 1 the depositional contact of the red and white Saugus beds (upper Pliocene) lying upon the 'basement' crystalline rocks is well exposed in the road cut. Note that the Saugus here lies directly upon the crystalline rocks, and that the Pico (Pliocene) and Modelo (Miocene) formations have been overlapped (see cross-section figure 5). Here the 'basement' complex consists of biotite and hornblende gneiss with conspicuous feldspathic layers and some amphibolite.

'Basement' complex

Part of the complex contains marble and graphite that are exposed to the west up Limerock Canyon, hence the gneiss probably was formed from a sedimentary sequence. The complicated folds indicate plastic deformation in association with plu-



tonic metamorphism. These gneisses, commonly migmatic, extend through a large part of the western San Gabriel Mountains. They have been intruded by younger granitic rocks of probable late Mesozoic age. The age of the original sediments represented by the gneiss may be Mesozoic, Paleozoic, or pre-Cambrian.

The geologic structure in the vicinity of Little Tujunga Canyon is shown in the cross section in figure 5. The late Tertiary and Pleistocene history of this part of the San Gabriel Mountains can be summarized as follows:

(1) Deposition of the Modelo, Pico, and Saugus formations (Miocene and Pliocene) upon the 'basement' complex with lapping of the younger sediments (Saugus) farthest to the northeast. Rock types within the conglomerates suggest that the San Gabriel fault was active during this time, and that it probably played a part in uplifting the source area.

(2) During Pleistocene time the area was compressed in a northeast-southwest direction, and the 'basement' complex with its veneer of sedimentary rocks was folded. With continued deformation the folds broke, and thrust faults such as the Lopez fault carried the 'basement' rocks out upon the Saugus formation. Folding of the crystalline rocks probably was achieved by slip on the many joints and fractures that are conspicuous in any good exposure.

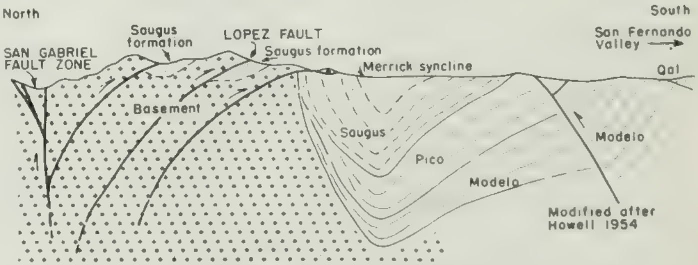


Fig. 5. Cross section through south flank of San Gabriel Mountains to San Fernando Valley.

For the next half-mile north of Stop 1, the Little Tujunga Canyon road follows the contact between the 'basement' complex on the right (east) and the Saugus sediments on the left (west). An excellent exposure of the Lopez fault is accessible by means of a dirt road on the west side of the high-

Lopez fault

way (Stop 2). Here the gneiss has been highly sheared and fractured, and has been faulted against the Saugus (Pliocene) formation. The contact, marked by a 2-inch zone of reddish fault gouge and a much wider zone of brecciation, is sharp and can easily be followed along the mountain front. Note the steepening of dip in the Saugus beds near the fault. Cobbles of anorthosite in the Saugus formation probably were derived from the large masses of anorthosite several miles to the north in the higher parts of the San Gabriel Range. The trend of the Lopez fault and its steep dip suggest that here it is a tear fault with a large strike-slip component, and marks the southeastern boundary of the Lopez thrust plate.

San Gabriel fault

Continuing up Little Tujunga Canyon, the road crosses the Lopez fault and then cuts through the 'basement' complex. At the first hair-pin turn, eight-tenths of a mile from Stop 2, is a good exposure of gneiss with steeply inclined layering. Past this turn the road crosses the top of a broad terrace and thence crosses a part of the San Gabriel fault zone. Stop 3 provides an excellent view of the San Gabriel fault and of the terrace deposits that lie unconformably upon both the Saugus formation and the 'basement' complex. Due west, a saddle on the skyline marks the course of the San Gabriel fault in that direction. From this saddle the fault crosses the road in the foreground, where it separates crystalline 'basement' rocks on the north from Saugus conglomerates on the south. Southeastward from Stop 3 the fault crosses the skyline through another notch, and thence extends through the central and eastern San Gabriel Mountains.

The San Gabriel fault is ordinarily defined by a fractured and brecciated zone as much as half a mile wide. Its course is nearly everywhere marked by canyons and saddles that have been developed in the sheared rocks. The fault trends in a northwesterly direction, subparallel to the San Andreas fault, and has been traced for a distance of about 90 miles. The matching up of source areas of anorthosite and norite pebbles and cobbles in conglomerates and breccias laid down along the fault in areas to the northwest suggests that there has been a right lateral separation of 15 to 25 miles since late Miocene time.

Terraces

To the south, planed surfaces are clearly discernible at several elevations, where they have been developed on the Saugus formation. These surfaces are of two types: 1) stream-cut, or erosional, terraces with very thin and discontinuous veneers of sediment on the underlying rocks, and 2) surfaces of stream-terrace deposits consisting of clastic rubble that was laid down unconformably on eroded surfaces developed on underlying Saugus or 'basement' rocks. Both types of surfaces have been deeply dissected, and now exist as remnants of much more extensive surfaces.

From Stop 3 to the top of the grade (1.5 miles) the roadcuts expose intensely sheared rocks of the 'basement' complex. Several terrace remnants are in fault contact with the crystalline rocks, and indicate deformation in late Pleistocene or Recent time. Note that a gray-white granodiorite lies in a wide zone between two branches of the San Gabriel

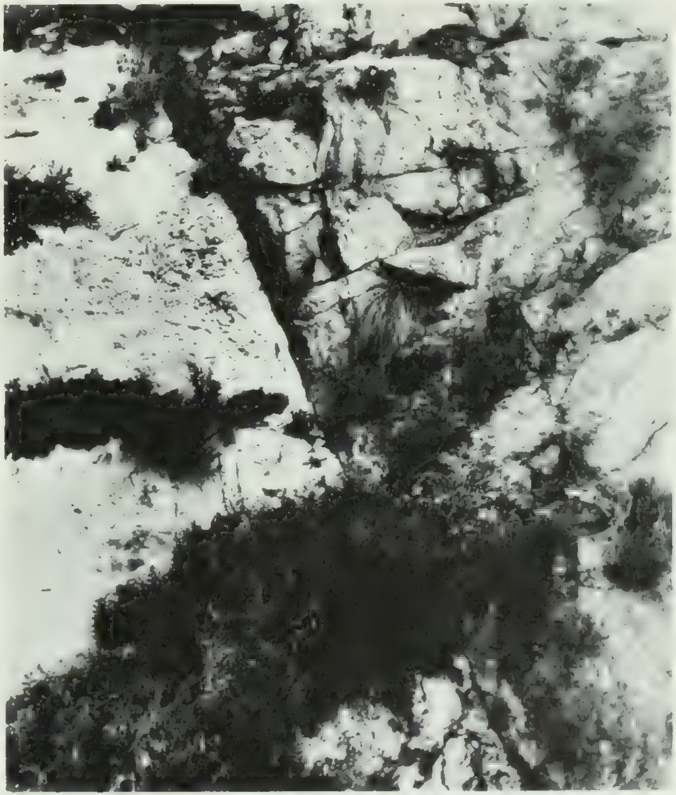


Fig. 6. Exposure of branch of San Gabriel fault showing dark metamorphic rocks faulted against light granodiorite. Width of exposure is about 25 feet. In San Gabriel Mountains off Little Tujunga Road. (Map 4, Stop 7).

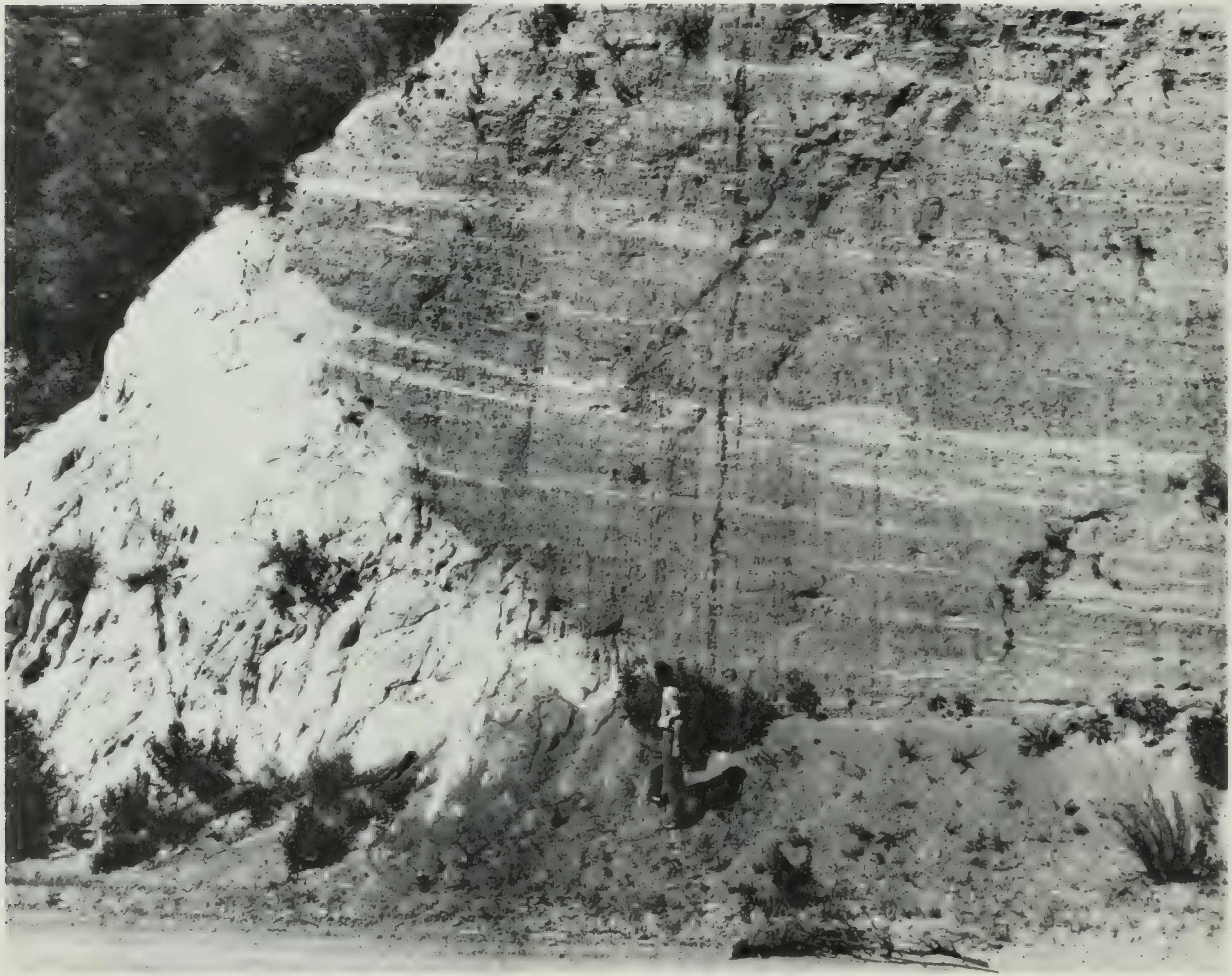


Fig. 7. Quaternary terrace sand and conglomerate deposits against white granodiorite in the San Gabriel Mountains. The overlapping contact exhibits a buttress type of unconformity. (Stop 6, Map 4).

fault. Within the granodiorite are numerous aplite dikes and masses of dark, nearly black, lamprophyres. In the canyons to the west excellent topographic expressions of the main San Gabriel fault can be seen. The top of the grade is the drainage divide between Little Tujunga and Pacoima Canyons (Stop 4). A sharp fault contact between dark-colored metamorphic rocks and the light-colored granodiorite is exposed on the side of the mountain north of the road. Excellent exposures of graphitic schist can be seen in a roadcut between the top of the grade and the bottom of Pacoima Canyon (see Map 4).

Older sediments

In the roadcut at Stop 5, a short distance northwest of the trout farm on Pacoima Creek, is a fine display of numerous dark lamprophyre and light aplite dikes cross-cutting the granodiorite country rock. Exposed in the roadcut just a few hundred feet from Stop 5 is a coarse, well-indurated conglomerate which is part of a sliver within the San Gabriel fault zone. The conglomerate is distinguished by clasts of purple and red volcanic rock and by cobbles derived from the 'basement' terrane. The occurrence of *Turritella pachecoensis* indicates a Paleocene age. In this same roadcut note that both the granitic and sedimentary rocks are capped by a terrace deposit. Several terrace deposits, lying unconformably on 'basement' rock, can be viewed as the road continues downhill. The trace of one of the main branches of the San Gabriel fault follows the gorge to the left (west).

At Stop 6 a Quaternary terrace deposit in contact with granodiorite exhibits a buttress type of unconformity in which the nearly horizontal terrace sediments curve slightly upward and abut against the steep face of the bounding crystalline rocks. Two-tenths of a mile northwest from Stop 6, in the elbow of a hairpin turn in the highway, a branch of the San Gabriel fault sharply separates dark metamorphic rocks from the light-colored granodiorite. The fault is easily traced along the hills to the east, and the contact can be viewed closely from a path leading from Stop 7.

Stop 8 affords a fine panoramic view of parts of Santa Clara River Valley, eastern Ventura basin, and Soledad basin. The Santa Clara River drains the Ventura basin westward for approximately 50 miles to the sea. The eastern part of the general basin area is transected by the San Gabriel fault, which separates the Ventura basin from the Soledad basin to the east. The fault passes through the Placerita oil field (silver-colored tanks near U.S. Highway 6), and continues northwestward into the mountains beyond Castaic.

View of Santa Clara River Valley

East of the San Gabriel fault, in the Soledad basin, are surface exposures of nearly 30,000 feet of mostly nonmarine sedimentary rocks ranging in age from Paleocene through Miocene. In general, these rocks form a southwest-dipping homocline that is exposed northward and northeastward from the San Gabriel fault to the Sierra Pelona, and eastward to points near Soledad Pass, not far beyond Map 5A. Nearly all of the rocks in the portion of the valley visible from this viewsite are nonmarine sandstone, conglomerate, siltstone, and tuff of the Mint Canyon (upper Miocene) formation. Broad, flat Quaternary stream terraces truncate the Mint Canyon beds along the banks of the Santa Clara River. The Sierra Pelona, the dark-colored ridge that lies due north across the valley, is composed of pre-Cambrian (?) schist flanked on the south by the Vasquez (Oligocene ?) and younger formations. West of the Sierra Pelona is the Ridge basin, where more than 20,000 feet of sedimentary rocks form what probably is the thickest uninterrupted nonmarine Pliocene section in North America.

The route continues down Bear Canyon to Sand Canyon and into the valley of the Santa Clara River. In the lower part of Bear Canyon the road crosses a prominent south-dipping fault that separates metamorphic rocks from norite (Stop 9). The norite exposed in the footwall is a very coarse-grained andesine-hypersthene rock, highly altered at this exposure. Extensive ilmenite-magnetite bodies occur in the norite in areas to the north and northeast. In 1927, when titanium minerals were first mined in California, some of the operations were in this part of the western San Gabriel Mountains. Production from these mines, however, was small.

SOLEDAD BASIN AND EASTERN VENTURA BASIN

MAP 5

Stratigraphy

The Soledad basin, northeast of the San Gabriel fault, was the site of nonmarine deposition during much of Tertiary and Quaternary time, but at least two marine invasions reached this area--one in late Miocene time, the other in Pliocene time. The low hills west of the Sand Canyon road display both marine and nonmarine formations of Miocene age, and these are in turn unconformably overlain by both marine and nonmarine Pliocene formations. Several northwest-trending folds extend through the hills

With the exception of the Castaic (upper Miocene), Towsley (Mio-Pliocene), and the Pico (Pliocene) formations, all of the units in the following chart (Fig. 8) are nonmarine deposits that occur in the Soledad basin northeast of the San Gabriel fault.

Vasquez formation:

The nonmarine Vasquez formation (Oligocene ?) crops out north and east of the area of Map 5 and over a large part of the area shown on Map 5A. The rocks are coarse, light-colored sandstones and conglomerates which lie with depositional contact upon crystalline rocks. A distinct reddish color becomes characteristic as the deposits increase in degree of consolidation and commonly in coarseness, south and east of Mint Canyon. Within the formation there are strong lithologic resemblances to the Sespe formation, which is widely distributed in the Ventura basin to the west. The sediments of the Vasquez formation were deposited in at least three localized fault-block basins, probably during the Oligocene epoch, and were severely deformed prior to deposition of the overlying Tick Canyon (lower Miocene) and Mint Canyon (upper Miocene) formations. Flows and sills of andesite and basalt are interlayered with the Vasquez strata south and east of Mint Canyon.

Tick Canyon formation:

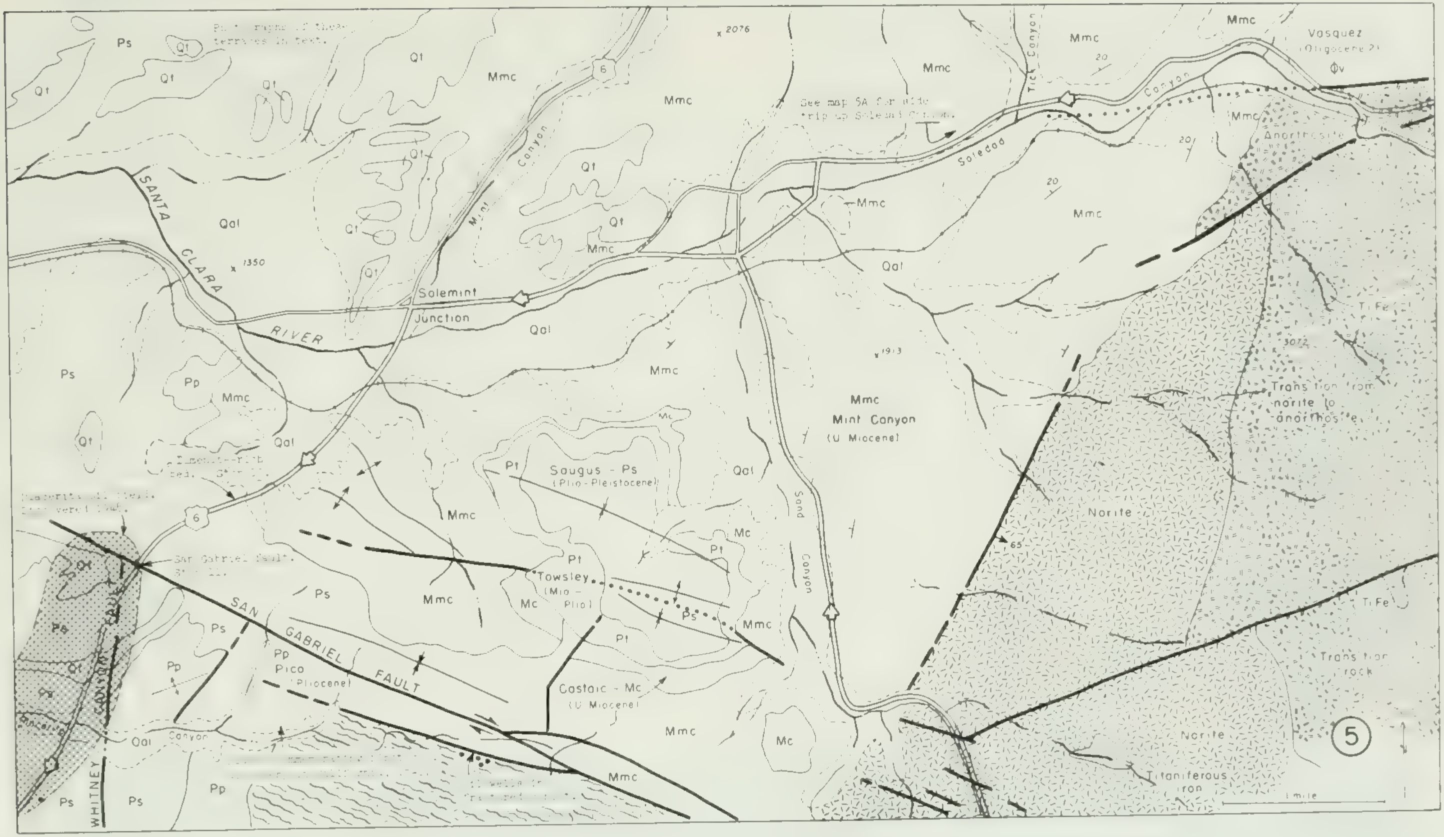
The Tick Canyon (lower Miocene) formation consists of reddish-brown clay, siltstone, and sandstone, with a poorly lithified boulder to pebble conglomerate at the base. The bulk of the section is fluviatile, but certain evenly laminated fine-grained beds are probably of lacustrine origin.

Age	Formation	Lithology & maximum thickness in feet
Recent and Pleistocene	Alluvium and Terrace gravels	Stream deposited sand and gravels
Pliocene	Saugus	Nonmarine gravel and sandstone 4,000
	Pico	Marine sandstone and shale 1,700
Miocene	Towsley	Marine shale and sandstone 4,000
	Castaic ("Modelo")	Marine sandstone, shale and conglomerate 500
	Mint Canyon	Nonmarine sandstone, conglomerate, siltstone, and tuff 4,500
	Tick Canyon	Nonmarine clay, siltstone, sandstone, and conglomerate 600
Oligocene (?)	Vasquez	Nonmarine. Coarse sandstone and conglomerate 14,000
		Basic volcanic flows and shallow intrusives 4,000
Pre-Cretaceous	Crystalline basement rocks	

Fig. 8. Formations exposed in the Soledad basin.

Mint Canyon formation:

The westward-dipping strata exposed in lower Sand Canyon and along the highway to Solement Junction are relatively coarse-grained members of the Mint Canyon (upper Miocene) formation. Vertebrate fossils from fluviatile beds and invertebrate and plant fossils from lacustrine sediments have been used for assigning the age, although there is some disagreement concerning the age significance of the vertebrate re-



mains. Older terrace deposits overlie the tilted Mint Canyon sediments with pronounced unconformity, and are in turn overlain by younger terrace deposits.

Castaic formation:

The Castaic formation (Crowell, 1954, this volume) consists of fossiliferous sandstones and shales that were correlated with the Modelo formation by Kew (1924). In the Soledad basin they are the only marine beds north of the Santa Clara River Valley. It has been suggested that this formation is interfingered with the Mint Canyon formation due to marine transgressive overlap, but the relations are not thoroughly understood.

Towsley formation:

The Towsley formation is the oldest rock unit recognizable on both sides of the San Gabriel fault in the vicinity of the Ventura Basin. This formation, of late upper Miocene and early Pliocene age, attains its maximum thickness along the north slope of the Santa Susana Mountains. It generally consists of a sequence of light-colored conglomerate and sandstone units interbedded with units of brown-weathering mudstone. The formation is about 4,000 feet thick near the Los Angeles-Ventura county line, and thins eastward to about 1,500 feet. It is overlapped by the Pico formation (Pliocene) three miles southeast of Newhall. Shallow-water near-shore deposits of the formation are preserved east of Newhall, but elsewhere evidence from faunas and from sedimentary structures indicates deep-water deposition of the coarse-grained rocks by turbidity currents (Winterer and Durham, 1954).

Saugus formation:

The Saugus formation here is composed of nonmarine gravels and sands that were deposited on a broad, westward sloping floodplain or series of alluvial fans. Although these beds are generally unfossiliferous, their marine analogues to the west yield invertebrates of late Pliocene and early Pleistocene age.

Fine-grained fluviatile and lacustrine beds of the Mint Canyon (upper Miocene) formation are exposed in roadcuts southwest of Solemint Junction along U.S. Highway 6. They are rather tightly folded. Dark-colored magnetite-ilmenite sands, exposed at Stop 10, occur near the base of the Saugus formation. The ilmenite probably was derived from the crystalline rocks of the San Gabriel Mountains, where masses of magnetite and ilmenite are associated with the anorthosite.

Placerita oil field

The Placerita oil field is the most prolific of a series of fields extending around the western end of the San Gabriel Mountains. The discovery of oil here in April 1948 was followed by a program of intensive drilling on town-lot subdivisions after the Spacing Act of California was declared unconstitutional in September 1949. The field thus was developed by a large number of closely spaced wells, which led to a high initial production and rapid decline. Production is obtained from two zones in Pico marine conglomerate, sandstone, and siltstone. A poorly defined anticlinal nose, flattened at depth to little more than a west-southwestward dip- on the north and against the Whitney Canyon fault on the east. ping homocline, is closed against the San Gabriel fault zone

From Stop 11, at the Placerita oil field, the trace of the San Gabriel fault is shown by a scarplet on the rounded hills southeast of the highway. The fault strikes northwest across the highway, and lies approximately between the two large reservoir tanks on the north side of the road. The Whitney Canyon fault intersects the San Gabriel fault in the Placerita

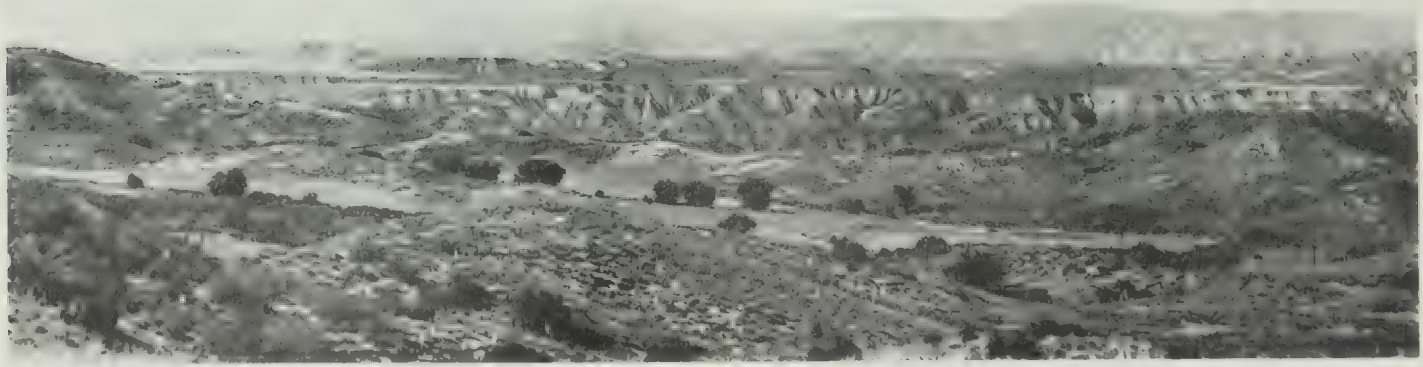


Fig. 9. Flat Quaternary stream terraces northwest of Solemint Junction as seen from U.S. Highway 6. Underlying nonmarine Mint Canyon (Miocene) beds have been subjected to several periods of planation by the Santa Clara River during Pleistocene time. Part of the Sierra Pelona rises in the background. (Map 5).

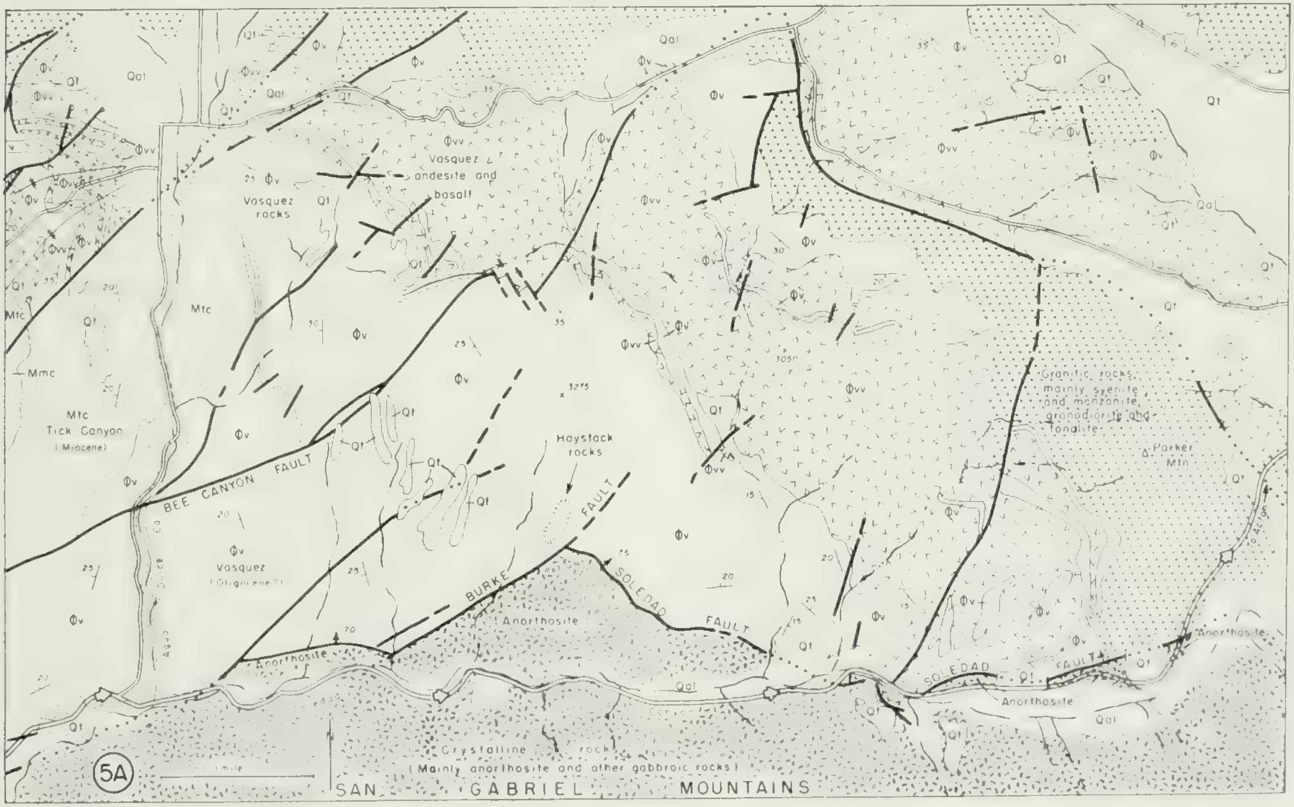
oil field, and trends southward, subparallel to the highway. The trace of this fault is poorly defined in this area, but easily can be seen farther south.

Roadcuts along U.S. Highway 6, between the San Gabriel fault and the Newhall turn-off, provide good exposures of cross-stratified Saugus deposits that dip northwestward and are unconformably overlain by much less indurated terrace gravels of similar composition. At Placerita Canyon a side road leads to the site of the 'Oak of the Golden Dream', where, in 1842, gold was discovered clinging to roots of wild onions. Farther up the canyon, wells that penetrated schist of the 'basement' complex have yielded small amounts of clear, kerosene-like oil which is believed to have migrated into the schist from oil-bearing strata in fault contact with the 'basement' complex.

MAP 5A

San Gabriel anorthosite

A side trip eastward into Soledad Canyon permits a close inspection of crystalline rocks of the San Gabriel Mountains, some of the older Tertiary strata of the Soledad basin, and the major fault zone that separates the basin from the San Gabriel Mountains on the south. About 4.7 miles east of the junction of the Sand Canyon road with the Soledad Canyon road (Map 5) is an exposure of white anorthosite intruded by dark lamprophyric dikes. Anorthosite, rare elsewhere in California, is extensively exposed for many miles along the lower north flank of the western San Gabriel Mountains. The rock consists typically of light-colored plagioclase and small percentages of chlorite, micas, and altered pyroxenes. Twinning planes are evident in the feldspar crystals, which com-


5A
1 mile
Vasquez andesite and basalt
Vasquez rocks
Φv
Φvv
Qal
Qt
Mtc
Mmc
Mtc Tick Canyon (Miocene)
Vasquez (Oligocene?)
BEE CANYON FAULT
BURKE FAULT
SOLEDAD FAULT
Haystack rocks
Granitic rocks, mainly syenite and monzonite, granodiorite and tonalite
Parker Mtn
Anorthosite
Crystalline rocks (Mainly anorthosite and other gabbroic rocks)
SAN GABRIEL MOUNTAINS

monly range from medium to coarse grained. Some of the crystals attain dimensions of several inches. To the south, across Soledad Canyon, is a good exposure of a fault that separates white anorthosite on the north from brown norite on the south.

After passing through a tunnel cut through highly sheared anorthosite and related rocks, one can observe similar light-colored 'basement' rocks on the south side of the canyon. High on the north side of the canyon is the Vasquez formation, here chiefly conglomerate with abundant cobbles and boulders of anorthosite. Between this conglomerate and the older rocks to the south is the Soledad fault, a major break that dips northward and trends essentially parallel to the canyon. This normal fault is here concealed beneath Quaternary terrace gravels, but it is plainly visible in a road cut a short distance beyond the tunnel.

Farther east, near the mouth of Agua Dulce Canyon, the road crosses Soledad Canyon, and for more than a mile beyond this point the Soledad fault can be seen low on the opposite slopes. On the higher slopes are spectacular steep-sided knobs of gray to pinkish brown Vasquez conglomerate, which here contains clasts of both anorthosite and granitic rocks. The strata dip westerly at low angles.

Approximately 5 miles east of the mouth of Agua Dulce Canyon the Soledad fault crosses to the south side of Soledad Canyon and is offset by several cross faults. Large roadcuts provide excellent exposures of these breaks, along which anorthosite, Vasquez conglomerate and breccia, and basaltic volcanic rocks are variously juxtaposed. A thick layer of volcanic rocks appears on the opposite side of the canyon where it is marked by low outcrops and somber brownish slopes. Most of these rocks are basaltic to andesitic flows, and some are markedly amydgaloidal.

Volcanic
rocks

The road crosses to the north side of the canyon immediately beyond this area and passes through several deep cuts in volcanic rocks and in highly sheared anorthosite. The trace of the Soledad fault lies immediately north of the road between this area and Ravenna, where it appears as a distinct line between white-weathering anorthosite and brown-weathering Vasquez strata. Immediately beyond and northeast of Ravenna, the lower part of the Vasquez section, comprising sandstone, coarse conglomerate and breccia, and two thick layers of volcanic rocks, lies with depositional contact upon the Parker Mountain quartz diorite. The trace of this contact passes through a prominent saddle high on the ridge north of the road. Several abandoned copper mines and prospects can be seen on the slopes of Parker Mountain between Ravenna and Acton.

Parker
Mountain
quartz
diorite

The canyon widens to a broad valley at Acton, immediately beyond the map area, and numerous gravel-capped terraces can be seen to the north and to the south. The hills that rise above these surfaces are underlain by Mesozoic plutonic rocks and Tertiary volcanic rocks. The road can be followed a few miles farther eastward to its junction with U.S. Highway 6, which extends through Soledad Pass into the Mojave Desert region.

MAP 6

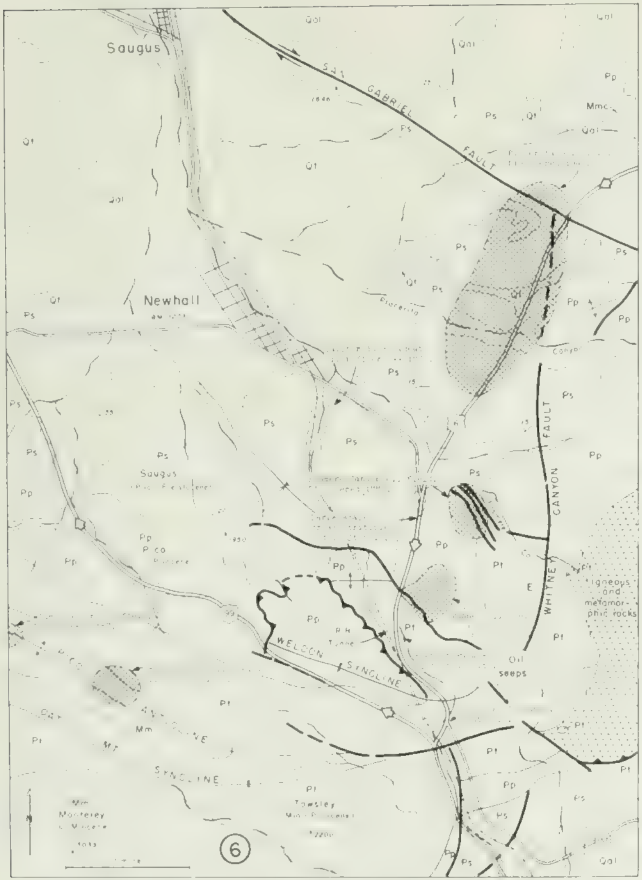
The oldest oil refinery in California, constructed in 1876, is just south of the town of Newhall, and has been partly restored as an historical monument. The refinery had a daily capacity of 20 barrels, and oil was hauled to it in wooden barrels from Pico Canyon.

The Elsmere Canyon field was discovered in 1889. Here, the oil accumulated in beds that lie against a northwest-striking fault that bounds the field on the north. Oil occurs both in basal Pliocene beds and in underlying rocks of middle Eocene age.

At Stop 12 large-scale cross-stratification within Pico beds is unusually well exposed in the deep roadcuts. These beds are believed to have been deposited under deltaic conditions during Pliocene time. The coarse-grained debris grades abruptly into fine-grained sandstone within a distance of one-quarter to one-half mile to the west. The contact at the north end of the series of roadcuts between massive sandstone and fine-grained sandstone is a thrust fault that dips 30 degrees to the southwest.

A small oil field, known as the Tunnel field, is located on a faulted homocline east of the highway. Oil sand occurs in marine beds of early Pliocene age, as well as in nonmarine strata that lie between Pliocene and Eocene rocks. Accumulation was controlled by faulting and by beds that pinch out in an up-dip direction.

South of the Tunnel oil field, U.S. Highway 6 parallels Fremont Pass. The vertical walls of this narrow pass through which Captain Fremont led his early California forces, are still discernible in the canyon a short distance of the highway. West of the highway, at the base of the imposing cliff, is a southwest-dipping thrust fault that involves Pliocene marine strata on both sides.



Stop 13 is slightly south of the northwest-trending axis of the Weldon syncline, which lies parallel to Weldon Canyon. Here oil-bearing sands of lower Pliocene age are exposed in the roadcut east of Foothill Boulevard (Highway 157) and near its intersection with U.S. Highway 6.

Continuing north along U.S. Highway 99, the route parallels the northeast flank of the Pico anticline, along which there are several small oil fields. These include, from east to west along the anticline, the East Canyon, Rice Canyon, Wiley Canyon, Towsley Canyon, DeWitt Canyon, and Pico Canyon fields, and collectively are known as the Pico anticline district of the Newhall oil field. Oil has been obtained from several zones in the Monterey (upper Miocene) formation, but production is now very small. In 1850 oil from natural seeps was crudely distilled in this area, and was used as 'burning oil' in the San Fernando Mission. This is believed to have been the first commercial production of oil in California.

MAP 7

Newhall
Potrero
oil field

The Pico Canyon and Newhall-Potrero oil fields are about 5 miles west of Highway 99, and are reached via the Pico Canyon road. The road is private in the Newhall-Potrero oil field. In the Newhall-Potrero oil field seven zones in upper Miocene strata contain oil on the limbs of a long, narrow, asymmetrical, northwest-plunging anticline. Reverse cross faults that strike nearly due east are encountered at depth. These faults displace strata from 50 to 300 feet.

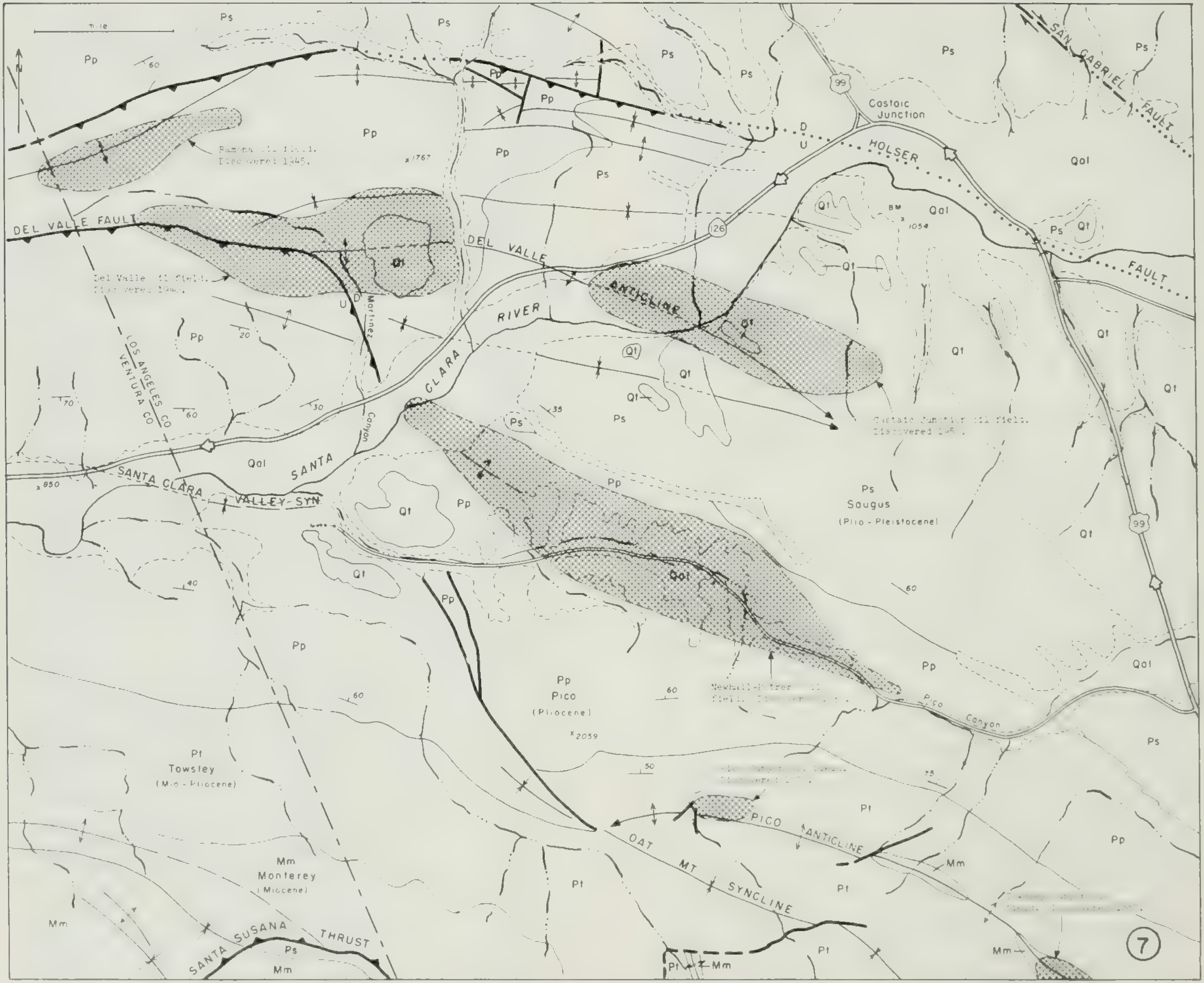
A short distance north of the turn-off to Pico Canyon, extensive terrace deposits of late Pleistocene age form the level skyline across U.S. Highway 99.

Where the highway crosses the Santa Clara River, a major south-dipping thrust fault, the Holser fault, is concealed beneath the alluvium. North of the bridge, in road cuts on the right (east) side of the highway, are steeply south-dipping nonmarine Pleistocene (?) gravels of the Saugus formation. The low hills to the northeast are composed of conglomerate, sandstone, and reddish-brown siltstone of the Saugus formation, and are transected by the San Gabriel fault.

Approximately a mile north of Castaic Junction is the Honor Rancho oil field, which is on property of the Los Angeles County prison farm. This anticlinal field, discovered in August 1950, has possible closure on the east against the San Gabriel fault. Oil is obtained from two zones in upper Miocene strata.

Castaic
Junction
oil field

About 3 miles southwest of Castaic Junction the axis of the Del Valle anticline is crossed. It is on this anticline that the Castaic Junction oil field is situated. The discovery well reached an oil zone at nearly 12,000 feet in January 1950. Production is from upper Miocene strata. The oil traps either are formed by strong cross-faulting in the area between the Del Valle and Castaic Junction fields, or are stratigraphic in nature, presumably in the form of lens-


mile
N
SAN GABRIEL FAULT
HOLSER FAULT
Castaic Junction
99
126
D
U
Ramona oil field. Discovered 1945.
Del Valle oil field. Discovered 1940.
DEL VALLE FAULT
DEL VALLE ANTICLINE
Martinez Canyon
SANTA CLARA RIVER
Castaic Junction oil field.
LOS ANGELES CO
VENTURA CO
SANTA CLARA VALLEY SYN
Ps Sougus (Plio - Pleistocene)
Pp Pico (Pliocene)
Pt Towsley (Mio - Pliocene)
Mm Monterey (Miocene)
Qal
Qt
Newhall-Potrero oil field.
Pico Canyon
PICO ANTICLINE
OAT MT SYNCLINE
SANTA SUSANA THRUST
x850
x1767
x2059
BM x1054
7

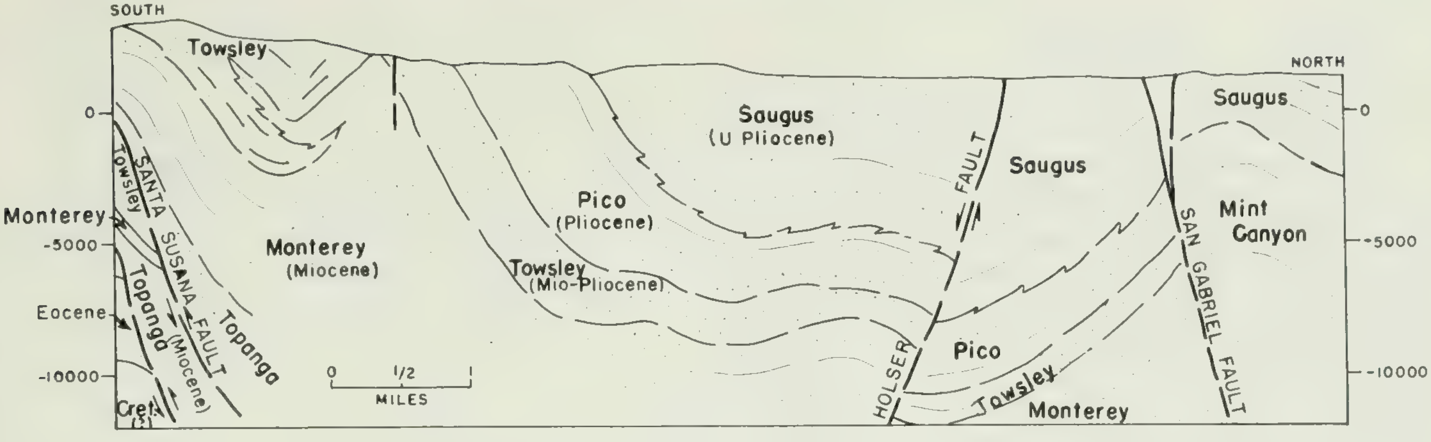


Fig. 10. Section across eastern Venture basin.

ing sands along the anticlinal structure.

Del Valle and Ramona oil fields

The axis of a major syncline is crossed just before one reaches Martinez Canyon. North and northwest of this canyon are the Del Valle and Ramona oil fields. The Del Valle field was discovered in September 1940, and yields oil from 10 zones in upper Miocene sandstone and conglomerate. The principal structure is the southeasterly plunging Del Valle anticline. The Ramona oil field lies northwest of the Del Valle field, and yields oil from three zones in upper Miocene strata. In this field the oil has accumulated in the Ramona anticline, but the traps are primarily stratigraphic. Both anticlines are confined to the block between the south-dipping Del Valle and Holser thrust faults. The trace of the Del Valle thrust fault appears as a small notch in the low hills north of Highway 126 and east of the Martinez Canyon road.

The northwest limit of the Newhall-Potrero oil field lies south of the highway. A well in this field near the road is believed to have penetrated the Del Valle fault zone.

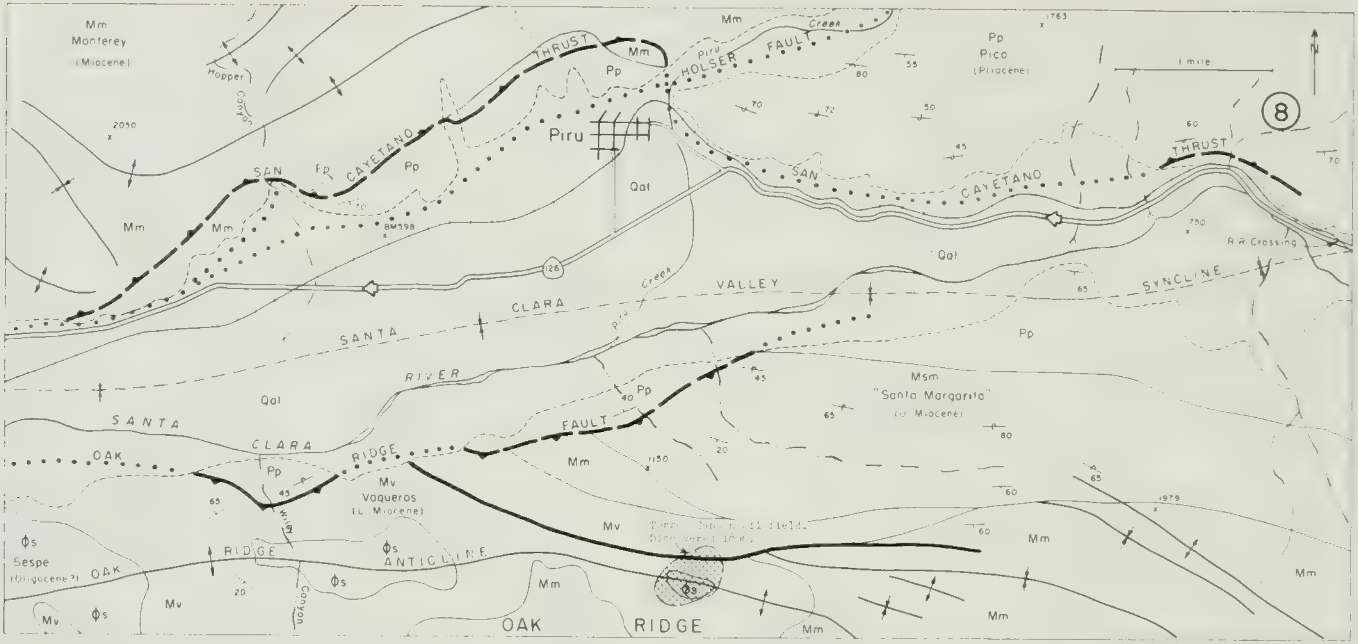
Toward the west the Santa Clara River Valley approximately coincides with the axis of the Santa Clara syncline, which extends westward for several miles. In the brush-covered hills on the south side of the river, Pliocene and upper Miocene rocks at least 10,000 feet thick dip steeply northward toward the center of the syncline. On the north side of Highway 126 the opposite flank of the Santa Clara syncline is exposed.

MAP 8

Looking to the southwest from the railroad crossing (east side of Map 8), one can see, high on the north flank of Oak Ridge, beds of white sandstone and brown siltstone of late Miocene age. Just beyond the railroad crossing, upper Pliocene fossils have been found in roadcuts in the white sandstone. Pliocene sandstone and conglomerate rise steeply north of Piru, and upper Miocene sedimentary rocks have been thrust over these by the San Cayetano fault.

Oak Ridge oil fields

Seven en-echelon anticlines form a chain approximately 20 miles long on the Oak Ridge uplift, which lies south of the Santa Clara River between Piru and Santa Paula. These anticlines, from east to west, are called the Oak Ridge, Torrey, Wiley, Shiells, Bardsdale, South Mountain, and West Mountain. All but the Wiley are productive. The South Mountain and Bardsdale fields are discussed in the text accompanying Maps 19 and 20. Commercial production began at the Tor-



rey field in 1896, more than half a century before production was developed from the Oak Ridge field in 1952.

Drag motion during thrusting of the south block of the Oak Ridge fault probably led to development of the folds. In the active fields on Oak Ridge, oil is obtained from several zones in the Sespe (mainly Oligocene) formation except in the Oak Ridge field itself, where the oil occurs in Miocene beds. In the Bardsdale field oil also is obtained from Eocene strata. The recent discovery of oil in new areas and from deeper sections in the Sespe formation in the old fields has prompted new wildcatting along the Oak Ridge thrust and has developed renewed interest in the old fields along the fault.

Santa Clara River Valley

The Santa Clara River Valley is a synclinal trough within a graben that lies between two opposed thrust faults--the San Cayetano thrust on the north and the Oak Ridge thrust on the south (see fig. 11). The location of these faults has been well established, even where they are covered by Recent alluvium of the Santa Clara River, because of the many penetrations of the fault plane by oil wells. Near Fillmore the surface traces of the two opposing thrust faults lie within a mile of each other! The San Cayetano thrust dips as gently as 20 degrees in places; the Oak Ridge thrust is generally steeper. In some places, relative movement from the north along the San Cayetano thrust has resulted in displacement of upper Miocene strata over rocks of Pleistocene or Pliocene age, and

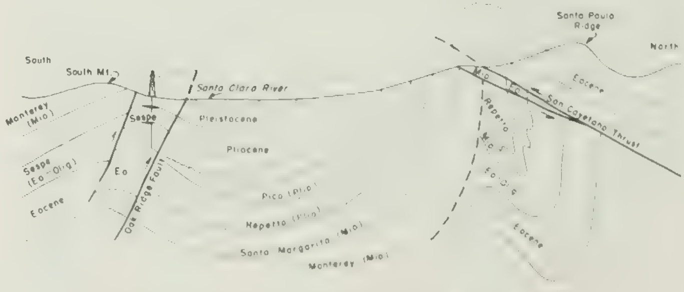


Fig. 11. Section across Santa Clara River Valley.

in displacement of upper Eocene strata over sedimentary rocks of upper Miocene or lower Pliocene age. Along the Oak Ridge thrust fault, upper Eocene sedimentary rocks lie against lower Pleistocene sandstone, gravel, and clay. Note that these two major thrust faults in the region dip in opposite directions!

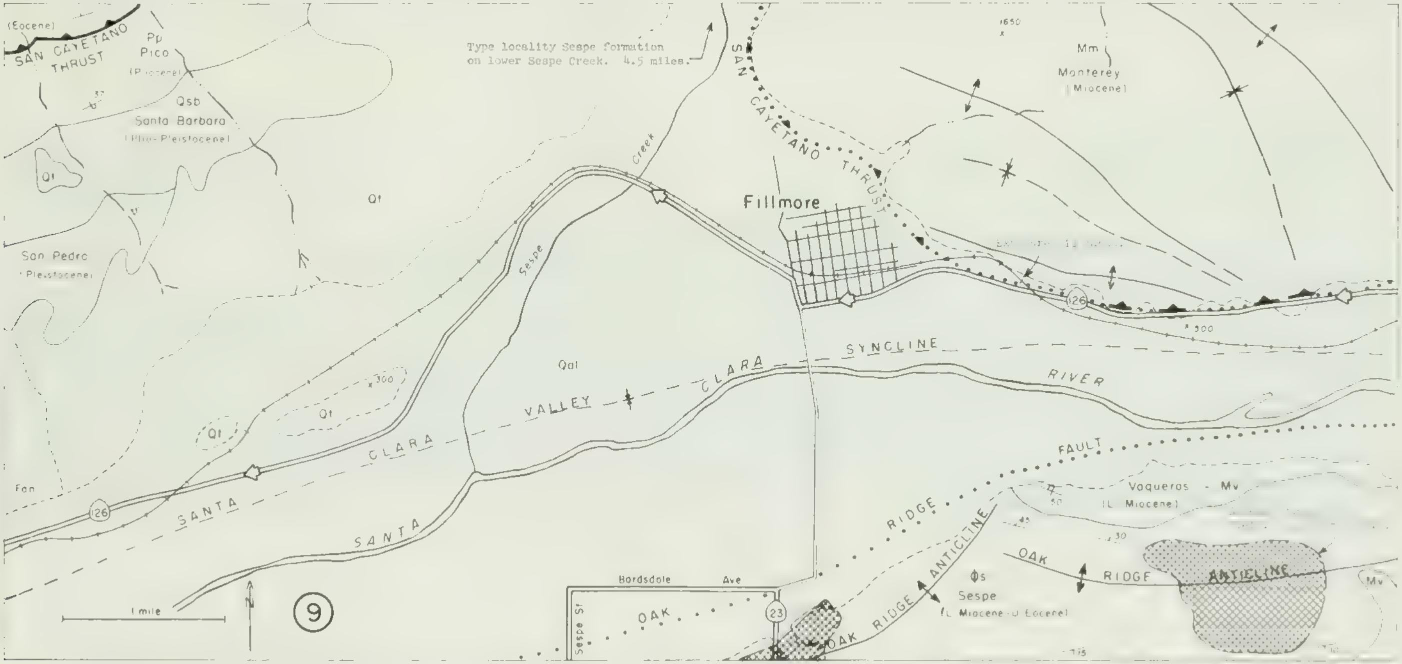
The Santa Clara River Valley is one of the major areas of citrus groves in California. Total value of the 1952 citrus crop from Ventura County, essentially the Santa Clara River Valley and Oxnard Plain, was approximately $38,000,000. One of the largest ranches in the valley is the Sespe Rancho. Originally an 1829 Spanish land grant to Carlos Carrillo, it now consists of 4,300 acres, about 1,300 of which are planted to citrus. The rancho currently employs about 300 people.

MAP 9

It is just within the east boundary of Map 9 that the surface traces of the San Cayetano and Oak Ridge thrust faults are closest together. Confined between them, but hidden by stream alluvium, is the axis of the Santa Clara Valley syncline.

Within a 3-mile radius of Fillmore, rocks that represent at least a part of every epoch since the beginning of Eocene time can be seen. To the northwest upper Eocene strata overlie middle and upper Pliocene rocks and Pleistocene beds. To the northeast are middle Miocene beds, and to the south, on Oak Ridge, Sespe (Oligocene) beds are present.

Six miles north of Fillmore, along lower Sespe Creek, is the type locality of the enigmatic Sespe formation. The variegated red, maroon, green, gray, and white sandstones and conglomerates of this formation are quite distinctive, and can be seen at many places in the Ventura basin. The strata are economically important as reservoir rocks for petroleum, and the oil probably migrated into them from marine rocks nearby. The formation extends in a nearly continuous belt for at least 100 miles eastward from near Point Conception, Santa Barbara County, to Simi Valley, Ventura County. It also crops out on Santa Rosa Island, in the central Santa Monica Mountains, and in the Santa Ana Mountains, and its probable correlative crops out in the Soledad basin and has been found



in well cores in the eastern part of the Los Angeles basin.

Sespe formation

The predominance of granitic pebbles and the absence or mere trace of ferromagnesian minerals suggest that the eastern part of the Sespe formation was derived from an area of granitic rocks, probably from a higher area that existed far to the east during Oligocene time. In the Lion Mountain area and westward from it, the Sespe formation contains a considerable amount of fragments derived from Franciscan (Jurassic ?) rocks. The color of the formation is attributed by some geologists to the development of lateritic clay soil under a prevailing tropical climate, but it has recently been pointed out that there is a noteworthy lack of fossil plant remains to support the supposition of a tropical environment of deposition.

Fossil remains of land mammals, including oreodont, rhinoceros, horse, and camel, have been collected from scattered localities. The absence of marine fossils indicates that little of the Sespe is marine, and the absence of fresh-water invertebrate remains suggests that it is not lacustrine. The mammalian fossils suggest that the Sespe formation was deposited during a broad time interval, extending from late Eocene to early Miocene. Some geologists, however, now believe that these fossils could have been transported, and hence that they do not necessarily represent the age of the strata in which they now occur. Furthermore, the meager vertebrate faunas are not diagnostic of the climate, environment, or mode of deposition of the Sespe formation. The real nature of deposition of these strata therefore is not clearly understood, and it still remains a problem to be worked out as more evidence is gathered and evaluated.

SANTA PAULA-OJAI VALLEY

MAP 10

Timber Canyon fan

Several Quaternary terraces are clearly discernible along the mountain slopes bordering the Santa Clara River Valley, as is the well developed alluvial fan at the mouth of Timber Canyon. Timber Canyon has been filled with detrital material derived from the steep scarp of the San Cayetano thrust that rises above it. This fan deposit is best observed from points on the opposite side of the valley, where it can be seen in its entirety.

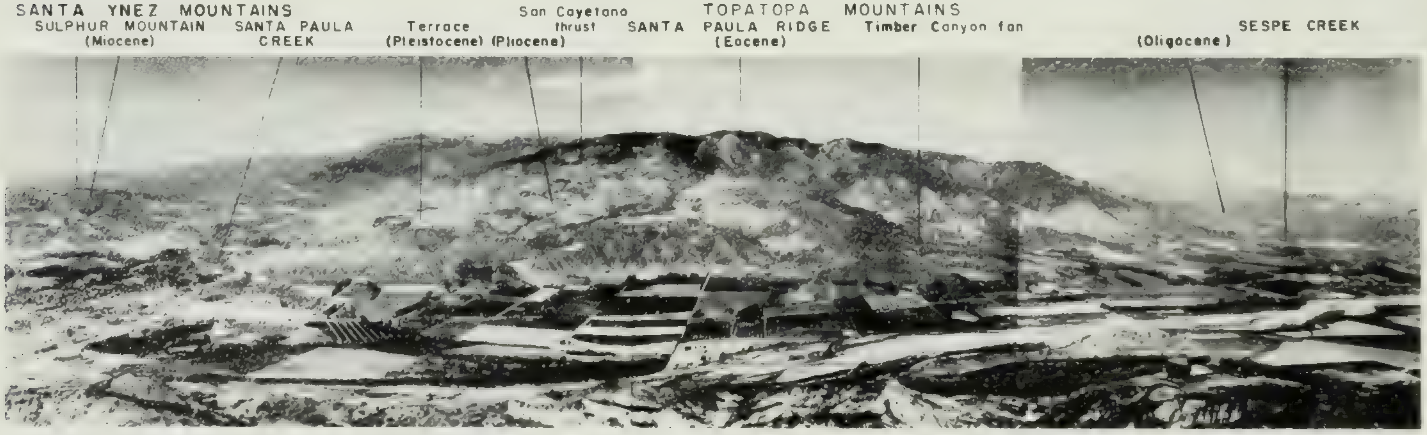
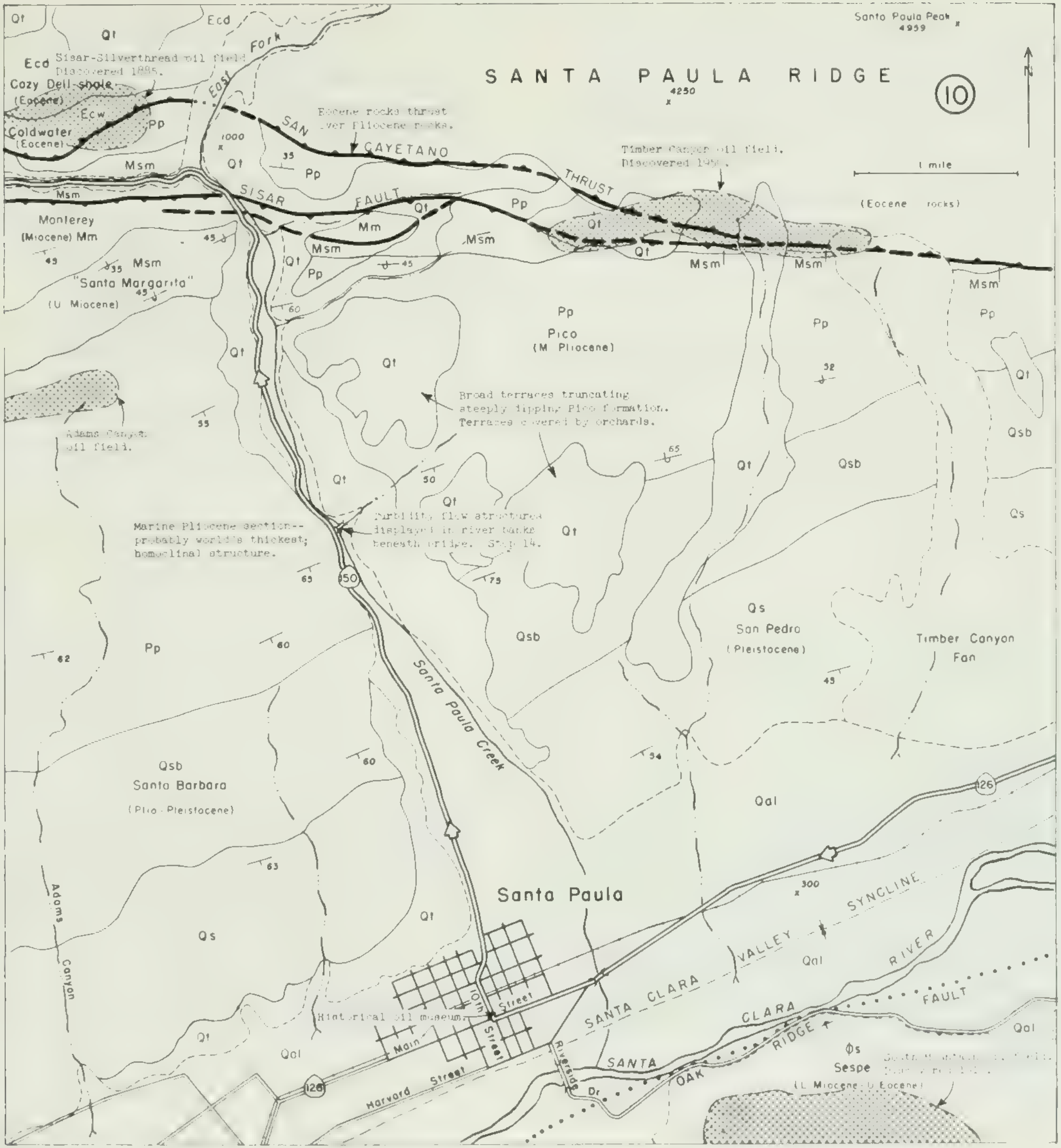


Fig. 12. View north across Santa Clara River Valley from the top of South Mountain. The valley is a synclinal depression between two opposing thrust faults. The San Cayetano thrust fault occurs along the change in slope below Santa Paula Ridge. Timber Canyon fan is outlined by the concentration of vegetation on its surface. (Maps 9 and 10).


Santa Paula Peak 4959
SANTA PAULA RIDGE
4250
10
N
1 mile
(Eocene rocks)
Qt
Ecd
East Fork
Sisar-Silverthread oil field. Discovered 1885.
Cozy Dell shale (Eocene)
Ecw
Coldwater (Eocene)
Pp
Eocene rocks thrust over Pliocene rocks.
SAN CAYETANO THRUST
1000
35
Msm
SISAR FAULT
Monterey (Miocene) Mm
Mm
"Santa Margarita" (U Miocene)
45
35
60
Timber Canyon oil field. Discovered 195
Pico (M Pliocene)
52
Broad terraces truncating steeply dipping Pico formation. Terraces covered by orchards.
Adams Canyon oil field.
55
65
50
Marine Pliocene section--probably world's thickest; homoclinal structure.
Turbidity flow structures displayed in river banks beneath bridge. Stop 14.
150
75
Qsb
Qs
San Pedro (Pleistocene)
Timber Canyon Fan
62
Santa Paula Creek
54
Qsb
Santa Barbara (Plio-Pleistocene)
Qal
126
63
Santa Paula
300
SANTA CLARA VALLEY SYNCLINE
Adams Canyon
10th Street
Historical oil museum.
Main Street
Harvard Street
Riverside Dr
SANTA CLARA RIVER
FAULT
SANTA CLARA
OAK RIDGE
Φs
Sespe (L Miocene - U Eocene)

Oil Museum

The California Oil Museum, on the corner of 10th and Main Streets in Santa Paula, is housed in the building where the Union Oil Company was founded in 1890. The museum contains equipment used in the early days of oil development in the region.

Santa Paula Creek Pliocene section

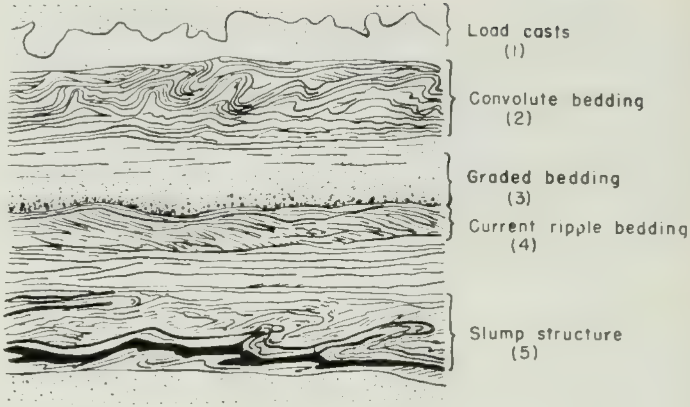
For 4 miles north along Santa Paula Creek, Highway 150 traverses, at right angles to the strike, an uninterrupted homoclinal section of Pliocene and Pleistocene deposits. The total thickness of this section is approximately 17,000 feet, of which about 12,000 feet comprises Pliocene strata. In Adams Canyon, 2 miles to the west, these sediments approach 20,000 feet in thickness, and are believed to form the thickest section of marine Pliocene and Pleistocene rocks in California, and one of the thickest in the world.

Turbidity-current structures

The Pliocene sediments contain many structural features that have been attributed to deposition in deep water by turbidity currents. Such subsurface currents contain sediments in suspension, and when once initiated flow along the floor beneath a body of still water owing to the greater density of the mixture of water and solid material. Turbidity-current structures are particularly well exposed in the banks of Santa Paula Creek at Stop 14. Sandstones, in thin layers interbedded with shale, are believed to have been first deposited in a deep marine basin several miles from the shore, and then later transported into the central and deeper parts of the basin by means of turbidity currents. Ecological studies of Foraminifera in the Pliocene Pico formation indicate that these beds were deposited in marine waters several thousand feet deep, certainly out of reach of near-shore sedimentation, and for this reason the turbidity-current origin for these beds appears most attractive. Examples of most turbidity-current structures such as graded bedding, load casts, pull-aparts, slump structures, convolute bedding, and current bedding can be observed in the banks of Santa Paula Creek.

Sulphur Mountain

Sulphur Mountain north of Stop 14, is essentially a south-dipping homocline of Miocene sediments locally overturned to the north. These structural relations are shown in figure 14. The bold escarpment on the south side of Sulphur Mountain, first interpreted as a fault scarp, is now thought to be an effect of differential erosion between resistant shale of the Monterey formation and the softer underlying shale of the 'Santa Margarita' formation.



After Kuenen 1953 & Shrock 1948

Fig. 13. Diagram showing types of sedimentary structures formed by turbidity currents.

(1) Load casts, pockets developed by plastic deformation of a bed by a later load.
(2) Convolute bedding developed during deposition of the bed by hydrodynamic pressure combined with loading in the troughs.
(3) Graded bedding in which the texture grades from coarse-grained particles in lower part of stratum to fine-grained particles in upper part.
(4) Current ripple bedding where particles were swept down slope by bottom turbidity flows. Indicates direction of flow from left to right.
(5) Slump structures due to horizontal movement of beds after deposition.

On each side of Highway 150 are conspicuous alluvial terraces formed by the ancestral Santa Paula Creek, which flowed southward. The various levels reflect periodic rejuvenations of the stream, which now is actively cutting downwards.

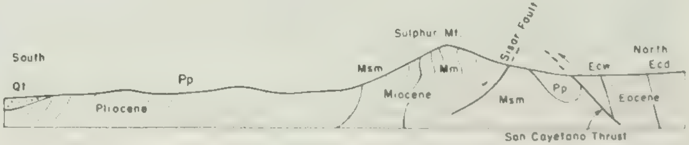


Fig. 14. North-south cross section through Sulphur Mountain.

The south-dipping Sisar fault, well exposed in the roadcut at the junction of the east fork of Santa Paula Creek and Sisar Creek, cuts the north slope of Sulphur Mountain, where it brings the Monterey formation in contact with the 'Santa Margarita' formation (fig. 14).

San Cayetano thrust

The San Cayetano thrust, traceable on the surface for more than 30 miles, enters the region east of Timber Canyon, crosses Santa Paula Ridge, and disappears beneath the alluvium of Ojai Valley. It probably dies out in the south slopes of Santa Paula Ridge, where hard Eocene (Matillija) sandstone of the upper plate forms a 2,000-foot scarp above the softer 'Santa Margarita' (Miocene) and Pico (Pliocene) shales at the base of the ridge. The Timber Canyon oil field is adjacent to the thrust west of the Timber Canyon fan. Within the field the fault dips approximately 55 degrees north, and has a minimum vertical displacement of about 8,000 feet. That the San Cayetano thrust probably is still active is shown by deposits of late Quaternary terrace gravels which have been faulted and back-tilted toward their source.

MAP 11

Oil seepages occur on the north side of Sulphur Mountain and along the base of the Topatopa Mountains. The seep at Stop 15 is reported to be the largest in California. Here heavy oil, accompanied by sulphurous water, flows down the side of the mountain from outcrops of fractured Miocene shales between the Sisar and San Cayetano faults. In the early 1860's several tunnels driven into the steep south slopes of Sulphur Mountain penetrated oil sands below the surface. This marked the first successful 'oil mining' in the western hemisphere.

Oil 'mining'

It is estimated that more than 30 tunnels with a combined length of about $2\frac{1}{2}$ miles were driven into the mountain. All the work was done by hand, and the tunnels were aligned and lighted by the use of mirrors and reflected sunlight. Caving ground and petroleum gases caused the deaths of several workers. Individual tunnels generally were less than 1,000 feet long, and a foot-board and a track ran their entire length. Also on the floor was a gutter in which the oil and water flowed down to a separating tank. It is reported that one of these oil tunnels yielded 900 barrels of oil per month when it was completed in 1889. A little oil still is being obtained from some of these tunnels today.

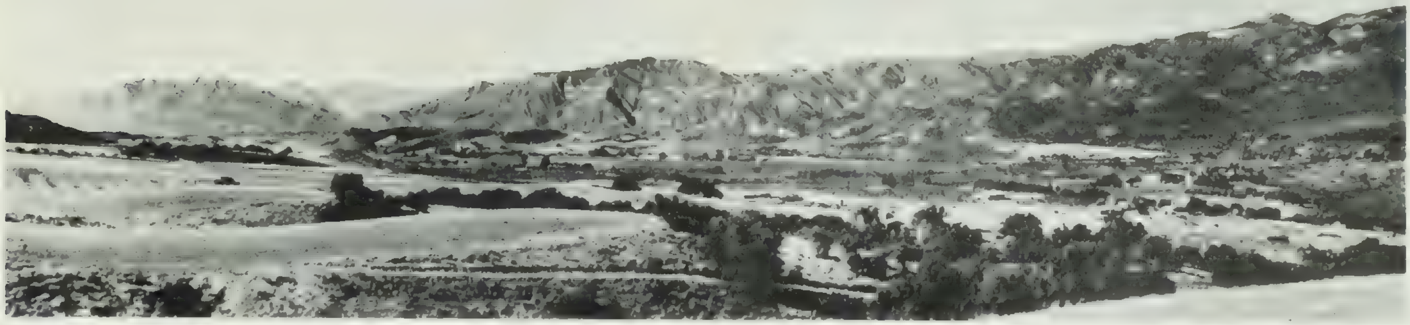
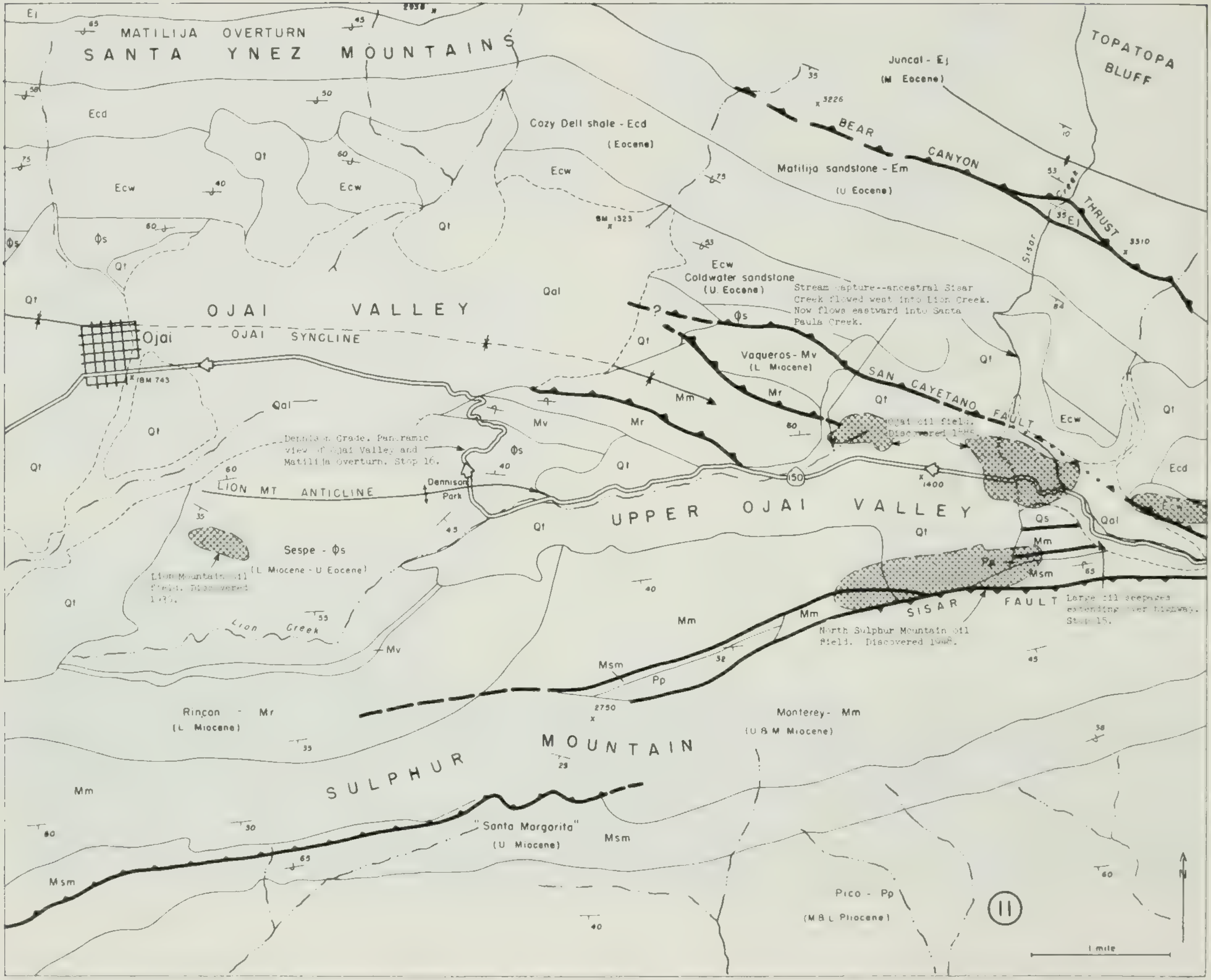


Fig. 15. Looking northwest across Upper Ojai Valley towards the eastern end of the Santa Ynez Mountains. The foreground is underlain by Miocene shales of the Monterey formation. White, north-dipping outcrops on the flank of the mountains in center of photograph are overturned Eocene sandstones. (Matilija Overturn). The prominent ridge on the left of the photograph contains the same strata dipping southward. (Map 11).



Stream capture--ancestral Sisar Creek flowed west into Lion Creek. Now flows eastward into Santa Paula Creek.

Dennison Grade. Panoramic view of Ojai Valley and Matilija Overturn. Stop 16.

Ojai oil field. Discovered 1865.

Lion Mountain oil field. Discovered 1935.

North Sulphur Mountain oil field. Discovered 1948.

Large oil seepages extending over highway. Stop 15.

Matilija overturn

The top of the grade west of Stop 15 provides an excellent view of the precipitous ranges of the Santa Ynez Mountains and the geologically complex area between this range and Sulphur Mountain. In the towering cliff-front of the Santa Ynez Mountains bordering Ojai Valley, the beds have been folded and overturned so that they dip north. This structural feature has been named the Matilija overturn, and is part of the south limb of the intricately faulted anticlinal fold, nearly 40 miles long, that lies on the southern slopes of the Santa Ynez Mountains. West of the Ventura River the beds again have a normal southern dip. Eocene formations are involved in the Matilija overturn. The prominent white ledge exposed at the base of the mountains is the Coldwater sandstone; it is bordered on the north by the older Cozy Dell shale (see cross-section). The Cozy Dell shale is in turn bordered on the north by the still older Matilija sandstone. Higher in the mountains, above the Matilija sandstone, the Juncal formation is locally upthrust along the Bear Canyon fault. Near Sisar Creek, the Matilija structure is broken by the San Cayetano thrust. The San Cayetano and Sisar faults converge still farther to the east, and several faults between them separate wedges of Miocene and Pliocene rocks.

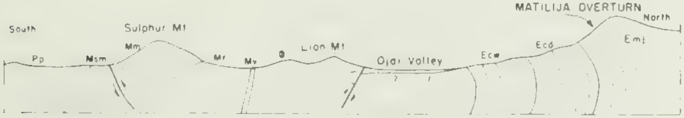


Fig. 16. North-south section showing overturned Eocene section and its relationship to rest of area.

Sisar Creek stream capture

At the east end of Upper Ojai Valley a fine example of Recent stream capture is displayed in the Santa Paula Creek-Sisar Creek-Lion Creek drainage system. High terraces suggest that the waters of what today is the East Fork of Santa Paula Creek once flowed westward (see fig. 17, I). Santa Paula Creek, eroding headward, captured first the East Fork (II), and then Sisar Creek (III).

The structure of the rocks beneath Upper Ojai Valley is obscured by terrace gravels, alluvial fans, and stream deposits, but well data indicate that it is essentially an east-plunging faulted anticline that is bounded on the north and south by thrust faults. At Dennison Park, near Stop 16, the highway crosses the axis of the Lion Mountain anticline (also known as Black Mountain anticline), the exposed core of which consists of red beds of the Sespe (mainly Oligocene) formation.

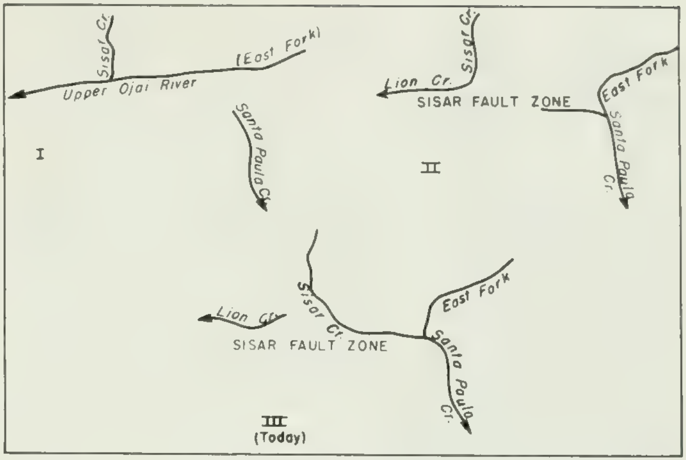


Fig. 17. Stages in capture of Sisar Creek by Santa Paula Creek.

Ojai Valley

Stop 16, on one of the turn-outs on Dennison Grade, provides an excellent view of Ojai Valley and the Santa Ynez Mountains. Ojai Valley is a structural depression, and, like Upper Ojai Valley, it is filled with Pleistocene and Recent stream alluvium more than 700 feet thick. Its structure is essentially synclinal, with overturned beds on each limb. The north side of the valley is bounded by the steep wall of the Santa Ynez Mountains. The overturned strata in the mountains can be traced westward to the Ventura River, where they are nearly vertical, and thence to points beyond where they revert to a normal south-dipping attitude. The alluvial fans emerging from the large canyons are excellent aquifers, and furnish most of the water supply for Ojai Valley.

WHEELER HOT SPRINGS - VENTURA

MAP 12

From Dennison grade the road passes through the town of Ojai (pronounced 'Oh-hi', an Indian word meaning 'the Moon'). West of Ojai turn right onto U.S. Highway 399 and proceed north to Wheeler Hot Springs. This 5-mile trip passes through a steep canyon whose walls permit a close inspection of the upper Eocene section. This section is mostly overturned as far north as the third tunnel in Wheeler Gorge, where the road crosses the Santa Ynez fault. The rocks to the north lie in their normal stratigraphic position.

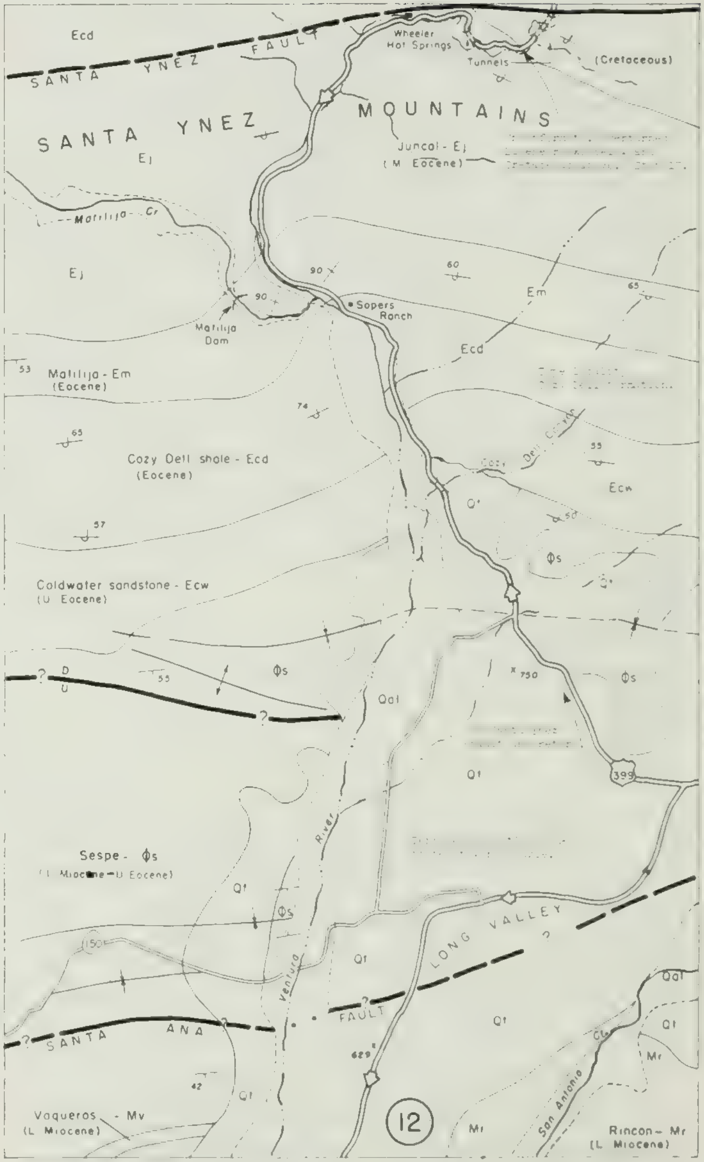
Series	Formation	Lithology
Oligocene	Sespe	Pink sandstone and conglomerate.
Eocene	Coldwater sandstone	Light-colored hard sandstone; fossiliferous; green and red shale.
	Cozy Dell shale	Gray shale with some sandstone.
	Matilija sandstone	Gray hard sandstone.
	Juncal formation Sierra Blanca limestone member.	Gray shale with minor sandstone layers.
Upper Cretaceous	Undifferentiated	Hard shale and sandstone, thin beds, with conglomerate layers.

Fig. 18. Rocks exposed in Ojai-Wheeler Hot Springs area.

The low foothills at the mouth of the canyon, whence the Ventura River issues, are underlain by red beds of the Sespe formation. On the west side of the highway these beds extend over the higher hills up to the skyline. The bold white outcrops at and near the skyline are beds of the Coldwater (Eocene) sandstone in normal stratigraphic position. Quaternary terrace gravels along the highway mask the contact of the Sespe formation with the light-colored sandstone and interbedded red shales of the Coldwater formation.

Eocene stratigraphy

At Cozy Dell Creek bridge, the gray shales of the Eocene Cozy Dell formation are well exposed. A tenth of a mile north of Soper's Ranch this formation is in contact with Eocene Matilija beds. This is the type locality of the Matilija formation. Note the narrowness and steepness of the canyon where it cuts the more resistant Matilija sandstone. The lowest unit of the overturned section, the Juncal (middle Eocene) formation, consists mainly of dark gray shale that contains thin layers of hard sandstone. The exposures of the Juncal formation extend from a point about three-quarters of a mile northwest of Soper's Ranch, past Wheeler Springs, to a point a short distance beyond the north portal of the first tunnel in Wheeler Gorge. Here the disconformable base of the Eocene section is marked by dark limy shale (Sierra Blanca member) in contact with Cretaceous shale (Stop 17).



Cretaceous conglomerate and interbedded dark shale are exposed between the south portal of the second tunnel and the third tunnel ahead. Note the rectilinear course of the creek at the tunnels, where strong control has been exercised by bedding and jointing in the resistant rocks. Large loadclasts and very thick graded beds are characteristic of the Cretaceous strata. Excellent current bedding is exhibited by the thin sandstone layers within the Cretaceous shales just north of the northern tunnel, and a Cretaceous ammonite has been uncovered in these hard black shales.

Santa Ynez fault

The Santa Ynez fault, which is traceable for more than 60 miles, crosses the highway a short distance north of the northern tunnel. Here overturned to the vertical, Cretaceous conglomerate and underlying black shale lie in fault contact with the Cozy Dell (Eocene) formation. The stratigraphic separation on the Santa Ynez fault at this locality is estimated to be 8,000 to 9,000 feet.

Warped terraces

Return to the mouth of the canyon of the upper Ventura River and follow Highway 399 south through the valley of the Ventura River to the coast. In this part of the route, conclusive evidence of intermittent uplift in Quaternary time and of continued deformation to the present time is provided by Quaternary terraces. These terraces, which may be seen at several levels along the river, are warped so that they are now inclined in a direction opposite to their initial seaward slope. Recent diastrophism is also indicated by faulted terraces and some Recent fault scarps. Terraces exist throughout the length of the Ventura River Valley, and a sequence of seven terraces is present in the area between Long Valley and San Antonio Creek (see Maps 12 and 13).

MAP 13

South of the town of Oakview, the Oakview terrace widens to a mesa, and rises from an altitude of 500 feet at Oakview to 550 feet at San Antonio Creek within a horizontal distance of less than a mile. This terrace is clearly back-tilted and continues to rise for a distance of 2 miles farther south. It can be recognized upstream and downstream from Oakview, and can be traced from the Santa Ynez Mountains to the sea. The creek is antecedent in that it maintained its course during the warping.

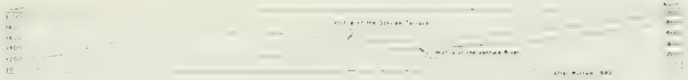


Fig. 19. Profile of Oakview terrace.

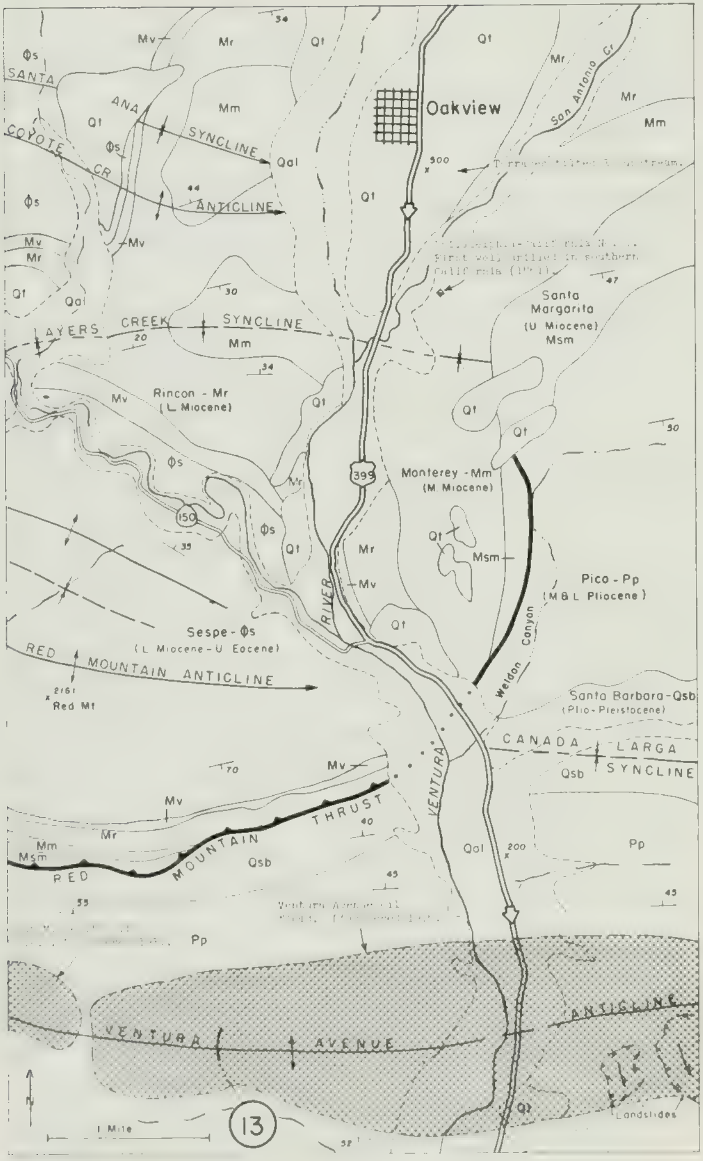
To the east, across San Antonio Creek, is the site of Philadelphia-California No. 1, considered to be the first well drilled in search of oil in southern California. This hole was drilled in the 1860's by the Scott interests of Pennsylvania (see Map 13).

Red Mountain anticline and thrust

One of the most prominent structural features south of Oakview is the doubly plunging Red Mountain anticline on the west side of Ventura River. This fold involves mainly red sandstone and shale of the Sespe (Oligocene) formation. The south side of Red Mountain is bounded by the Red Mountain thrust, which extends westward for 10 miles and separates older Tertiary rocks from an extremely thick section of Pliocene marine sedimentary rocks. East of the highway the thrust swings northward and apparently dies out as a tear fault. North of the Red Mountain thrust the Pliocene section is very thin and incomplete, whereas 13,000 feet of conformable marine Pliocene strata lie with discordance upon Pliocene beds south of the fault, and locally lie with great angular unconformity upon older Tertiary rocks. Lower Pliocene rocks were once deposited north of the Red Mountain thrust, but were largely eroded away as a result of mid-Pliocene orogeny.

From the Red Mountain thrust southward to the sea the exposed strata are entirely Pliocene in age, except for a narrow strip of Pleistocene beds of the San Pedro formation and the upper 1,000 feet of the Santa Barbara formation just north of Ventura (Map 14). This extremely thick Pliocene section, the same as that viewed in Santa Paula Creek, has been folded into the Cañada Larga syncline and the Ventura anticlinal system, which includes the Ventura Avenue and Rincon anticlines. This uplift is traceable for 18 miles from a point near Santa Paula to Punta Gorda on the coast northwest of Ventura (Map 17), where the anticline passes out to sea. The Cañada Larga syncline disappears beneath the Red Mountain thrust.

Numerous oil derricks, natural gas plants, compressor houses, and storage tanks of the Ventura Avenue oil field dot the steep slopes of the Ventura Avenue anticline on both sides



of the highway and in the bed of the Ventura River, which cuts across the axis of the fold. This field is now the second largest source of oil in California. As early as 1903, nine wells were drilled to a depth of about 400 feet from points in the river bed, and supplied the city of Ventura with natural gas for a short period. Gas escaping from a crushed zone near the area where the Ventura River crosses the axis of the anticline later led to exploratory drilling, and the discovery well, State Consolidated Oil Company's 'Lloyd' 1, was completed in 1916.

Ventura
Avenue
oil field

The early drilling, done almost entirely with cable tools, was seriously hindered by high gas pressures that caused caving holes, heavy flows of water, and blowouts. In 1930 heavy muds and rotary drilling equipment were successfully used, and subsequent development proceeded rapidly. Wells drilled to 14,000 feet bottom in rocks no older than early Pliocene, and by mid-1953 only one well, the Shell Oil Company's 'Taylor No. 378', had penetrated the base of the Pliocene section. This well, about a mile and a half west of the Ventura River, is in Miocene beds at a depth of about 15,000 feet.

Eight producing zones have been recognized to date; several are more than a thousand feet thick. Three major subsurface thrust faults in the crestal area of the anticline cause some of the oil zones to be repeated, one of them as many as four times. Productive limits of the field still are not completely defined. Many other thrusts have displacements ranging from 20 to 500 feet, and they commonly serve as barriers for accumulation of oil. The thrusts probably have been folded, but none appears to extend to the surface. There are 900 wells in this field, and the present production amounts to about 84,000 barrels daily. More than 448 million barrels of oil had been produced to January 1, 1953.

Because the 40,000- to 50,000-foot section of Tertiary and Quaternary rocks in the Ventura-Ojai region is essentially conformable, the Ventura Avenue anticline and Canada Larga syncline could not have existed until after deposition of San Pedro strata in early Pleistocene time. The San Pedro beds, containing Equus teeth, have consistent south dips of 35 to 60 degrees on the south flank of the Ventura Avenue anticline, and clearly were involved in the main Coast Range (Pasadenan) orogeny. Marine terrace deposits that are nearly horizontal or dip only 5 to 15 degrees south rest with extreme angular unconformity upon the San Pedro formation in the northern part of Ventura. These deposits contain an upper Pleistocene vertebrate fauna includ-

Pleistocene
Coast Ranges
orogeny

ing Equus and mastodon remains. Thus, the main orogeny of the Coast Ranges took place in middle Pleistocene time, after deposition of the San Pedro formation and before deposition of the terrace deposits that now are tilted.

The brief time involved and the recency of the folding in the Ventura region constitute one of the most striking geologic features in the state. In addition, the occurrence of 4,000 feet of steeply folded lower Pleistocene marine strata and 13,000 feet or more of Pliocene sedimentary rocks is worthy of particular note, as it seems to be unique in the United States.

MAP 14

Extensive landslides in Ventura Avenue oil field

Extensive landslides are common on the steep slopes within the Ventura Avenue oil field, and have damaged or ruined a large number of wells. Elaborate protective measures are now being used to safeguard wells in or adjacent to these areas. These efforts are concentrated on minimizing water percolation into the slides, and removal of water contained in the slides, or both. Several hundred nearly horizontal borings ('Hydrauger' holes), totaling more than 40 miles in length, have been drilled in the slides to remove water from them. The most evident measure taken to minimize water percolation is the stripping of vegetation from the sliding ground. Some slides are covered with oiled surfaces, several of which extend over as much as 160 acres. Some of them on the east side of Ventura Avenue can be seen from the highway. Wells were damaged by landsliding movement as long ago as 1926, and old topographic maps show that some of the slides were in existence long before the oil field was discovered.

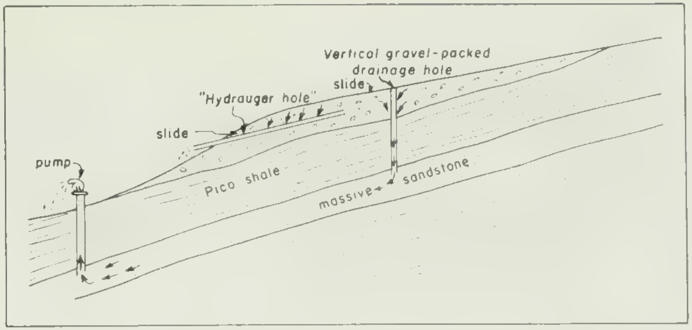


Fig. 20. Diagrammatic sketch showing method by which water in landslide is drained utilizing massive sandstone unit underlying slide.

Especially severe damage to wells was caused by landsliding during the winter of 1941-1942. In one 8-hour period a slide extending over an area of 60 acres moved 100 feet. Twenty-three wells either were sheared off beneath this slide or were so much distorted that their casing was badly bent and production was cut off. All the wells were later restored to

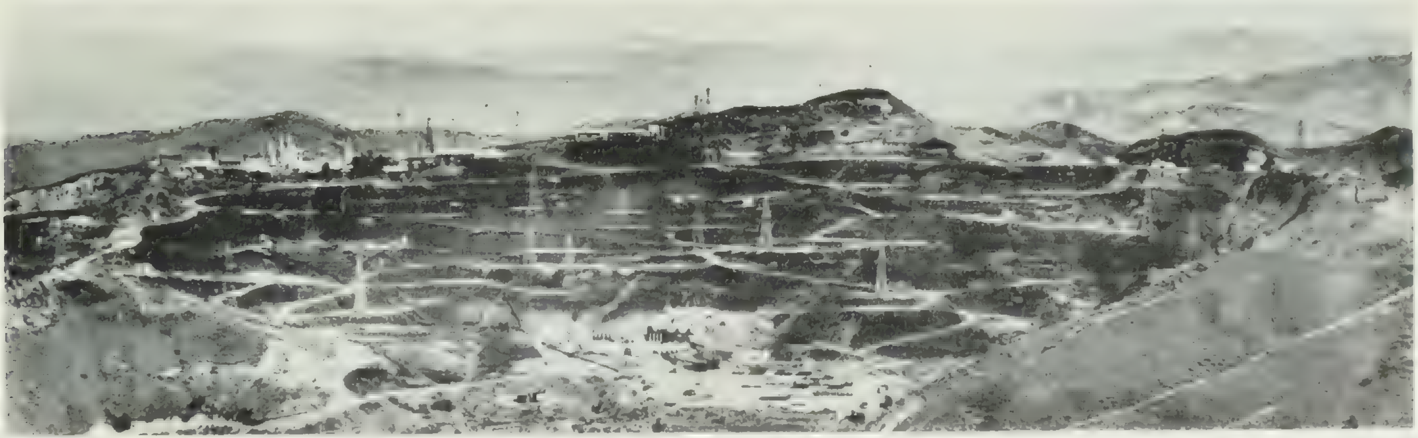
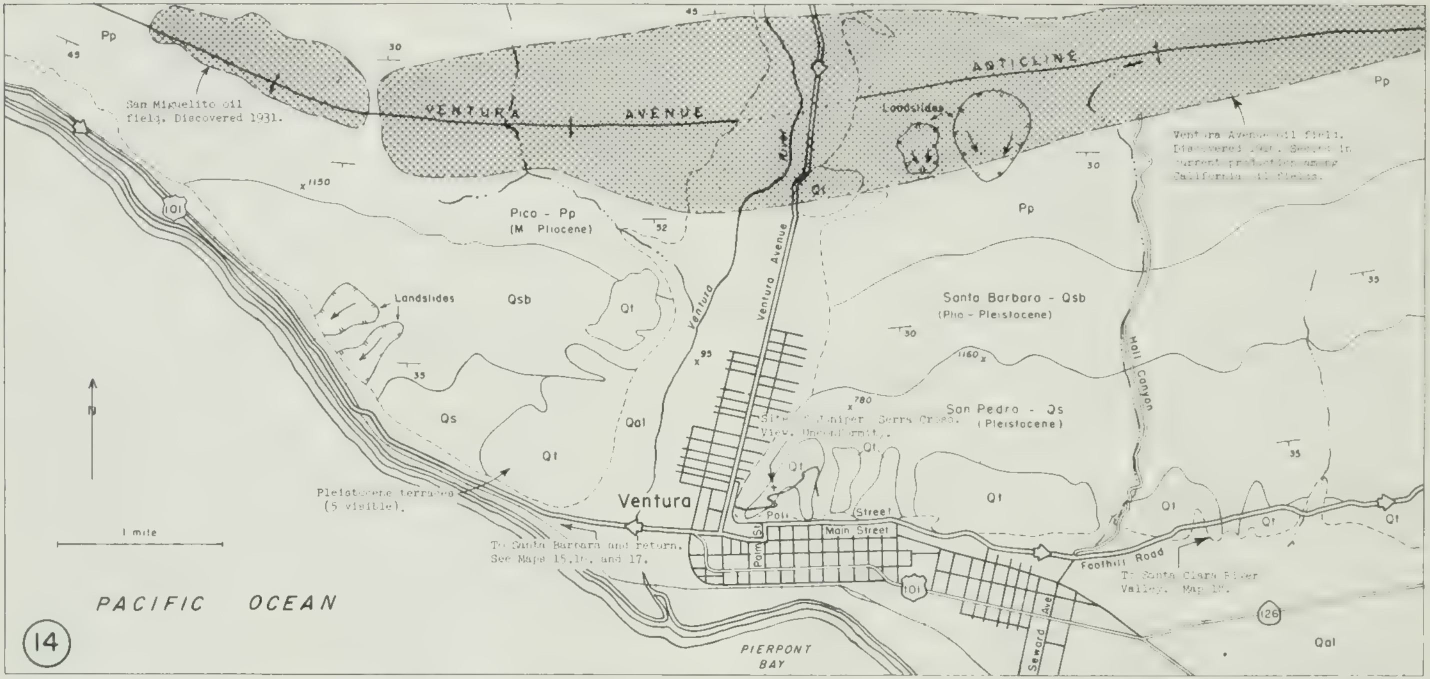


Fig. 21. Landslide in Ventura Avenue oil field. Surface of slide covering approximately 160 acres, has been contoured and oiled.


Pp
49
San Miguelito oil field. Discovered 1931.
30
45
VENTURA AVENUE ANTICLINE
Landslides
Pp
Ventura Avenue oil field. Discovered [illegible]. Second in current production among California oil fields.
30
101
x 1150
Pico - Pp (M Pliocene)
52
River
Qt
Pp
Ventura
Ventura Avenue
Landslides
Qsb
Qt
Santa Barbara - Qsb (Plio - Pleistocene)
30
35
x 95
1160 x
Hall Canyon
35
N
Qs
Qal
x 780
Site of Junipero Serra Cross. View. Unconformity.
San Pedro - Qs (Pleistocene)
Qt
35
Qt
Qt
Pleistocene terraces (5 visible).
Ventura
Poli Street
Main Street
Palm St
Qt
Qt
Qt
1 mile
To Santa Barbara and return. See Maps 15, 16, and 17.
Foothill Road
To Santa Clara River Valley. Map 18.
101
Seward Ave
126
PACIFIC OCEAN
PIERPONT BAY
Qal

14

production by digging vertical shafts 25 to 130 feet through the slide to reach the cut off parts of the holes. A massive sandstone bed below the slide-plane is now utilized as an aquifer into which water is drained (see sketch, fig. 20) by drilling vertical holes through the slide.

Additional 'Hydrauger' holes were drilled into the slide in a nearly horizontal position to further drain the mass, and the surface of the slide was scraped and oiled.

All of these precautions can only keep movement to a minimum and widen the time interval between major slips. Recent movements in the slides of the Ventura Avenue oil field are considered to be confined mostly to their upper parts, and the continual work on combating these vast areas of sliding ground is considered to be successful.

From the landslide areas on top of the Ventura Avenue oil field, proceed to the city of Ventura by way of Hall Canyon (see Map 14) or by way of Ventura Avenue. Hall Canyon provides a close view of part of the thick section of rocks that overlie the producing zones of the Ventura Avenue oil field. The Pliocene sedimentary rocks here consist of about 8,000 or 9,000 feet of alternating sandstone and shale, with a small thickness of coarse conglomerate. The foraminiferal species so abundant in the conglomerate indicates a marine depositional environment in waters 1,000 feet to 2,500 feet deep. The coarse conglomerate in this series of fine-grained sandstone and shale is believed to have been transported in submarine landslides or sandy mudflows. Near the mouth of Hall Canyon are south-dipping beds of the Santa Barbara formation and San Pedro formation, which are truncated by prominent terraces. Mastodont remains have been found in these terraces, and fossil horse teeth (Equus occidentalis) have been recovered from local terrace deposits exposed in streetcuts in Ventura.

Hall
Canyon

Ventura shifting shoreline

The shoreline features at Pierpont Beach, just south of Ventura, have changed markedly during the past hundred years. Littoral currents force the Ventura River to deposit most of its sand in the concavity of the shoreline between the deltas of the Ventura and Santa Clara Rivers. Comparison of U.S. Coast and Geodetic Survey field sheets for 1855 and 1933 shows about 580 feet of seaward advance of the shoreline during this time interval.

From Ventura the observer can next proceed along the route proposed on Maps 15 through 25, or Maps 18 through 25, or he can follow the briefly described route along the coast via U.S. Highway 101 to Santa Monica.

VENTURA TO LOS ANGELES VIA COAST HIGHWAY (ALTERNATE ROUTE)

U.S. Highway 101 Alternate (Roosevelt Highway), from Ventura to Santa Monica, provides one of the many beautiful coastal drives in southern California. From Ventura to Point Mugu it crosses the Oxnard Plain, which is noted for its lima bean ranches and citrus orchards. From Point Mugu to Santa Monica the highway skirts a series of towering cliffs, marine terraces, and beaches that display an unusually diversified array of shoreline features.

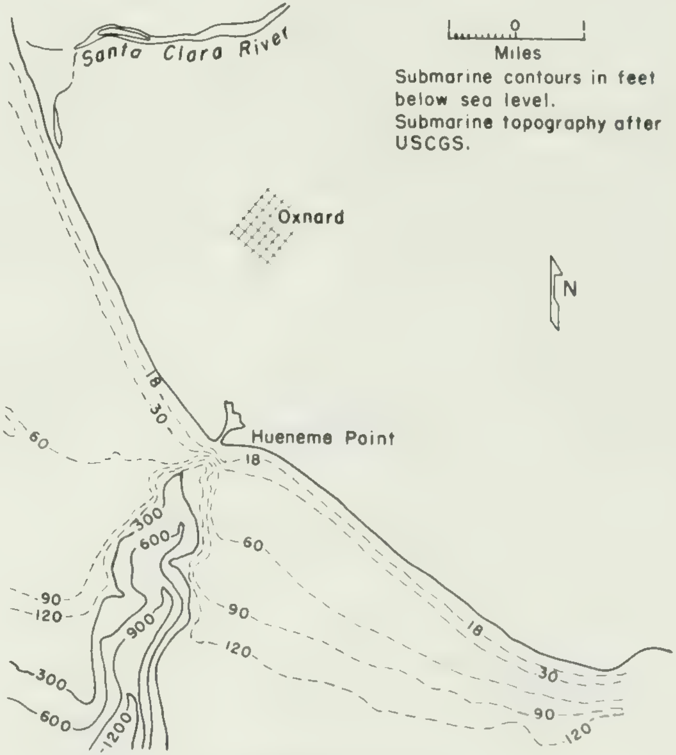
Oxnard Plain

The Oxnard Plain is the delta plain of the Santa Clara River. Drill records show that the alluvium generally is a few hundred feet thick, and overlies Pleistocene and Pliocene sedimentary rocks. Near Camarillo, about 9 miles northeast of Oxnard, the surface of the plain has been recently folded into elongate hills, and alluvium that antedates this folding can be traced across their crests. Subsurface Pleistocene strata generally dip parallel to the surface of the hills. Intensive pumping of ground water in this area has caused a lowering of the water table to points below sea level, and subsurface sea water is beginning to encroach inshore beneath the lush agricultural lands.

Submarine canyons

Several submarine canyons head against the seaward edge of the Oxnard Plain. The Hueneme Submarine Canyon, at the entrance to Port Hueneme, is approximately 13 miles long and cuts into upper Pleistocene and older rocks. Some geologists believe that such canyons are formed by erosion when sand, which accumulates in the head of the canyon by the action of longshore currents, slides seaward into deep water from time to time. Other geologists believe that the submarine canyons were cut subaerially during the geologic past, but this explanation seems unlikely here because there is no record of a suitable river during late Pleistocene and Recent time, when much of the canyon cutting must have been done. Several submarine canyons, similar to Hueneme, notch the steep offshore scarp at Point Mugu, and a very steep and rugged canyon is just off Point Dume.

Rocks of the Topanga (middle Miocene) formation are exposed in highway cuts just north of Point Mugu. These consist of sandstone and shale, and are cut by basaltic dikes and sills that also are of middle Miocene age.



Submarine contours in feet below sea level.
Submarine topography after USCGS.

Fig. 22. Hueneme submarine canyon.

Channel Islands

Looking seaward from Point Mugu on a clear day, one can see two of the four Santa Barbara Channel Islands, as well as San Nicolas and Santa Barbara Islands. The Channel Islands are a seaward continuation of the Santa Monica Mountains, which recently have been partly submerged leaving the higher mountain peaks as islands. Remains of Pleistocene elephants have been uncovered on Santa Rosa Island. These were dwarf types which probably were isolated on the island, and degenerated through inbreeding. Wild boars roam the islands today, and are a more recent acquisition. They were brought to the islands in the domesticated state by early Spanish explorers, and subsequently became wild.

East of Point Mugu the deep highway cut exposes black shale and fossiliferous sandstone of the Vaqueros formation. These are intruded by basaltic dikes and sills. Sedimentary structures in these rocks, such as graded and current bedding, suggest deep-water deposition by turbidity currents coming from the south. To the east along the highway, numerous remnants of uplifted Quaternary marine terrace deposits rest with angular unconformity on the strata of the Vaqueros and Topanga formations. The wide uplifted marine terrace surface at Dume Point, plainly visible from a distance, is underlain by siliceous and diatomaceous upper Miocene shales (Modelo), which are in fault contact with Topanga volcanics, sandstones, and shales (middle Miocene) at the landward edge of the terrace bench.

The remaining 12 miles eastward to Santa Monica crosses a region complicated by numerous faults and folds that are in part concealed by dense vegetation. Highway cuts expose sedimentary rocks of the Modelo (upper Miocene), Topanga (middle Miocene), Sespe (Oligocene ?), and Martinez (Paleocene) formations. The beds stand vertically in many places, as back of Malibu La Costa.

SANTA BARBARA AND VICINITY

MAP 15

Stop 18, atop Lavigia Hill, affords a good view of geologic features in the region surrounding Santa Barbara. Sedimentary rocks of middle Eocene to Recent age occur in the vicinity of Santa Barbara, and extend eastward to Ventura and westward to Point Conception. Marine Eocene strata form most of the central part of the Santa Ynez Mountains, a prominent unit of the Transverse Ranges, for their entire 75 mile length. These mountains approximate the northern boundary of the Ventura basin.

Santa Barbara area stratigraphy

Nearly all of the geologic formations, folds, and faults are roughly parallel to the trend of the Santa Ynez Mountains in the vicinity of Santa Barbara. The mountains are bordered on the north by the Santa Ynez fault, the same west-trending fault that appears north of Wheeler Hot Springs, and along which considerable lateral movement has occurred. Tertiary sedimentary rocks of middle Miocene and earlier age are continuously exposed along the foothills and the main ridge of the Santa Ynez Mountains. They are present but are not well exposed in the lower hills and beneath terrace deposits along the shore. They total about 14,500 feet in maximum thickness west of Santa Barbara, and locally are complexly folded and faulted. In one area only, about 6 miles west of Santa Barbara, do middle or lower Pliocene rocks crop out. Elsewhere the Santa Barbara formation (Pliocene-Pleistocene) lies with marked angular unconformity on pre-Pliocene beds. The older Pliocene beds have thus been removed by erosion as a result of mid-Pliocene orogeny.

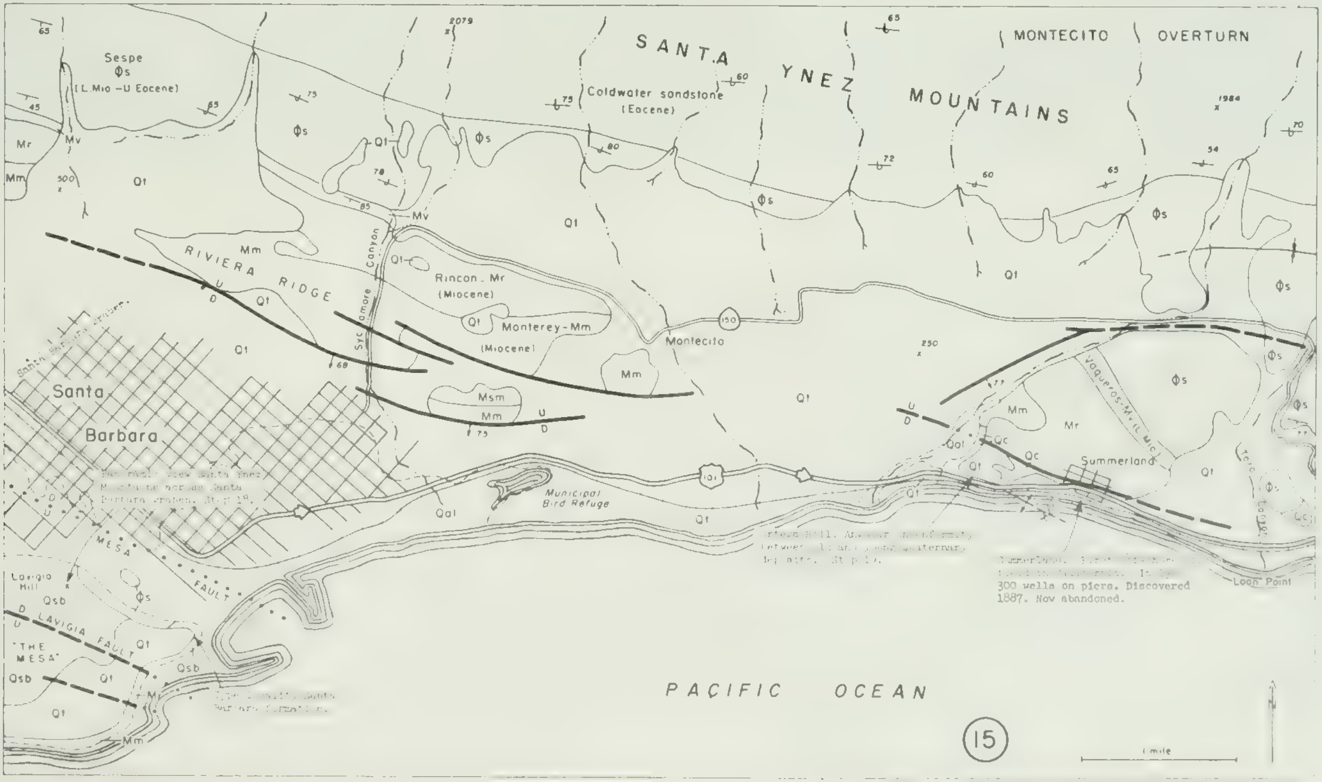
On the south flank of the Santa Ynez Mountains the Matilija, Cozy Dell, and Coldwater formations (upper Eocene) are overlain by the red beds of the Sespe (mainly Oligocene) formation. The Sespe formation also crops out in a few places along the north side of the 'Mesa', immediately southwest of the city of Santa Barbara. The type locality of the Santa Barbara (Pliocene-Pleistocene) formation is near the beach and east of Stop 18. Atop Lavigia Hill fossiliferous marine sand, silt, and clay contain a megafauna that indicates a shallow-water environment during deposition.

The structure of the south-coastal part of Santa Barbara County consists mainly of an anticlinal arch, in the Santa Ynez Mountains, modified by several minor folds and several major faults. The faults are considered to be younger than the folds because they offset some of them. The main faults trend west or slightly northwest; another set trends northeast. The horizontal component of displacement on faults west of Santa Barbara probably equals or exceeds the vertical component. Along most of the faults the vertical component of displacement amounts to several thousand feet, with the south side moved relatively upward. The principal movement on these faults occurred in middle Pleistocene time, and some of them are still active. On the south side of the Santa Ynez Mountains the Montecito Overturn extends from north of Santa Barbara eastward to a point nearly due north of Rincon Point. The whitish outcrops of the overturned (north-dipping) Eocene strata are much more prominent than the red beds of the Sespe (mainly Oligocene) formation that are present in the foothills. West of Santa Barbara the beds are in their normal stratigraphic position, and the Sespe formation is exposed much higher in the mountains.

The Santa Barbara graben, a trough overlain by Recent alluvium and terrace deposits, is the west-trending elongate depression in which the city is located. It is bounded by Riviera Ridge on the north and the 'Mesa' on the south. Quaternary terrace deposits, which lie upon Monterey shales in the Riviera Hills, are truncated by branches of the Sycamore Canyon fault system on the north side of the graben. On the 'Mesa', warped marine deposits of the Santa Barbara formation unconformably overlie Sespe red beds, and both sets of strata are truncated on the north by the Mesa fault.

The construction of the Santa Barbara breakwater has caused a large volume of sand to accumulate on the beach to the west. The beach just to the east has supplied much of this sand, but has been replenished by sand dredged from the harbor. Protective groins have been constructed on a sand-starved beach farther east. As much as 1,000 cubic yards of sand per day has been accumulated behind the breakwater. The beaches as far east as Carpinteria have been affected by the construction of this breakwater.

At Stop 19, east of Santa Barbara, the roadcut shows a 30-degree angular unconformity between lower Pleistocene nonmarine sand and gravel and the overlying nonmarine terrace deposits. This is another example of Recent deformation



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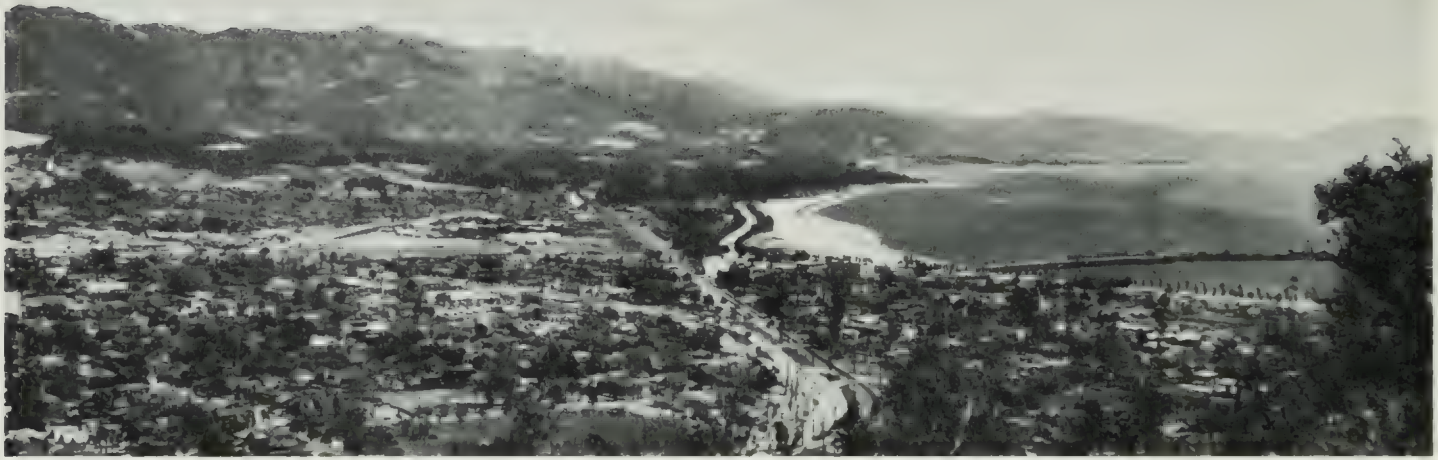


Fig. 23. View from Stop 18 atop Lavigia Hill, looking northeast across the Santa Barbara graben (left foreground) towards the Santa Ynez Mountains. In center of photograph the south flank of the Santa Ynez Mountains is bounded by the Arroyo Parida fault. The high peak on the right is Rincon Mountain. (Map 15).

and deposition in the Ventura basin. From this hill can be seen the cuspate spit that forms Sand Point near Carpinteria. This is an unusual coastline feature in this part of the state, for the entire accumulation of sand forming the point appears to be an effect of a wave shadow produced by submerged, resistant Miocene rocks that crop out on the sea floor just off the point.

Summerland oil field

From Ortega Hill a few remaining pilings of the Summerland oil field can be seen along the coast to the east. This field, discovered in 1887, is one of the oldest in the state and was the first to be developed in the open ocean; several other offshore fields have since been developed in Santa Barbara and Ventura Counties. In 1900 three hundred wells were producing an average of 5 barrels per well per day from Pleistocene and upper Pliocene beds at depths of 100 to 800 feet. This is one of the few known occurrences of oil production from Pleistocene beds. Wells were drilled in 1928 to deeper zones in Miocene strata, but these did not prove to be commercial. Production gradually declined, and the field eventually was shut down. The wells were drilled on a northeast-trending seaward-plunging anticline that is closed against a fault near shore, and yielded a total of more than 3 million barrels of 14 to 22 degree gravity oil.

MAP 16

Carpinteria Basin

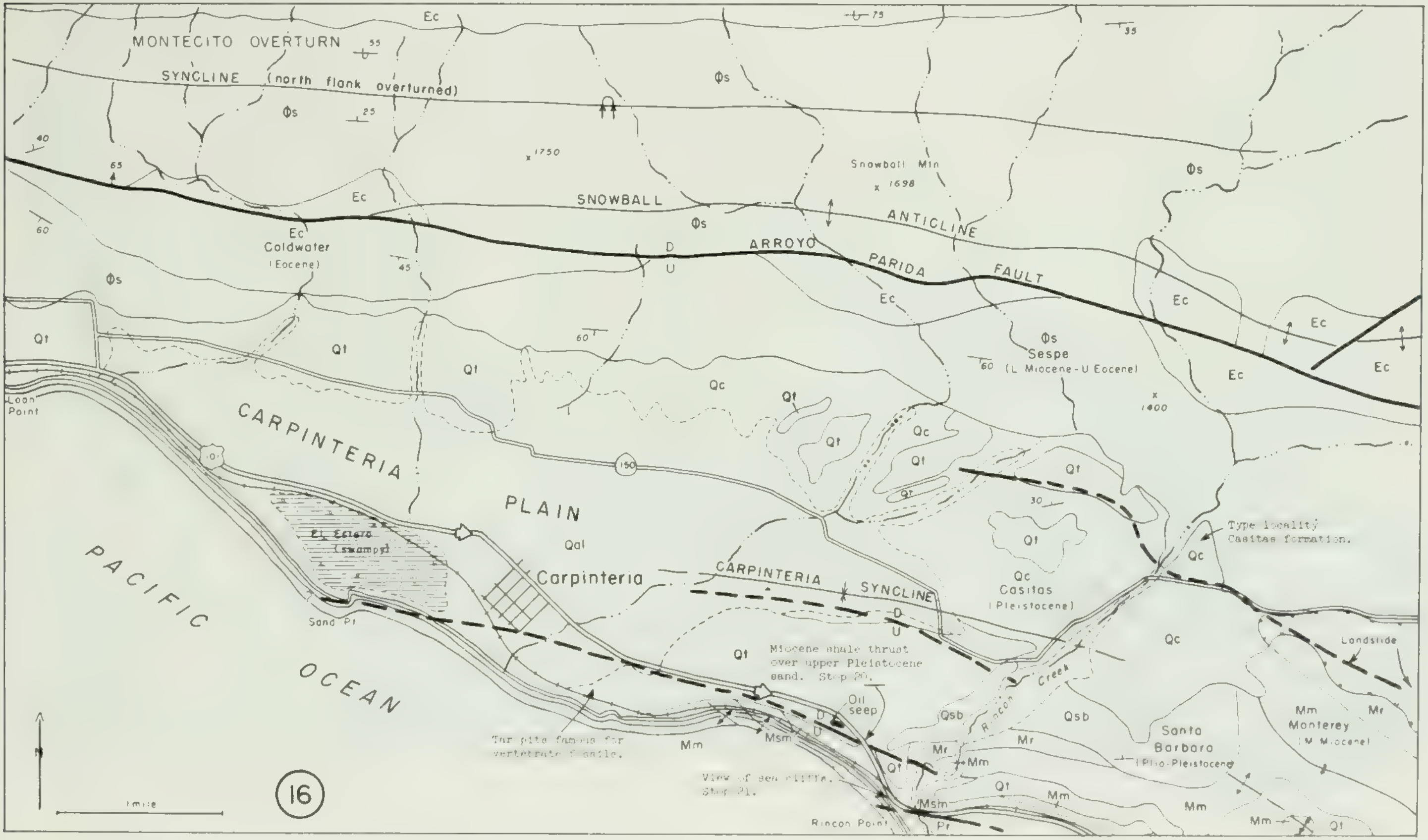
The Carpinteria Basin is the small alluvial plain surrounding the town of Carpinteria. 'Carpinteria' is the Spanish name for carpenter shop, and was applied by Spaniards who found Indians building tar-caulked boats here. Brea pits south of town probably were the source of the tar and evidently determined the location of the boat-building activity. These pits have yielded fossil remains of Pleistocene vertebrates, which were removed from the pits before they became the site of the city dump. The brea pits were formed by oil seeping upward from underlying Miocene shale into marine terrace deposits.

Sands and gravels of the Santa Barbara formation underlie much of the Carpinteria Basin, and are overlain by the nonmarine Casitas and marine Carpinteria formations (Pleistocene), and by Pleistocene alluvium. The type locality of the Carpinteria (upper Pleistocene) formation is southeast of Carpinteria, and these beds contain a Pleistocene flora where they are exposed along the sea cliffs. The Carpinteria formation is included as part of the Quaternary terrace deposits on Map 16.

The Casitas formation stratigraphically underlies the Carpinteria formation, and although more extensive in its occurrences, it is confined to the Carpinteria Basin area. It consists of moderately deformed, red continental deposits that are nearly 600 feet thick. They overlie the Pliocene-Pleistocene Santa Barbara formation. The Casitas and Santa Barbara formations are folded into a syncline in this basin, and the Pleistocene alluvium has been warped and dips slightly southward. The plain is surfaced with Recent alluvium deposited by streams that extend over the plain.

The slough west of Carpinteria is a warped portion of the Carpinteria plain in which marine mud and silt have been deposited. The depression containing the racetrack, east of Carpinteria, is a trough or sag pond along the trace of a south-dipping fault that extends into the basin from Rincon Creek. Tar seeps east of the racetrack are formed by the migration of oil from underlying Miocene strata upward along the fault plane.

The deep roadcuts at Stop 20 expose folded and overturned shales of the Monterey (middle Miocene) and Santa Margarita (upper Miocene) formations. These faulted beds have been thrust northward over unconsolidated Pleistocene sand, and indicate the recency of deformation in the region. A thin veneer of younger terrace deposits overlies this struc-



ture. From a parking area at Stop 21 an anticline in Miocene strata can be seen in the sea cliff to the northwest. Much of the low sea cliff, a short distance to the northwest, is made of natural asphalt. This material was formerly mined.

Rincon Point terraces

By looking eastward toward Rincon Mountain (Map 17) the observed can see a series of marine terraces that have been tilted seaward. Ten levels have been recognized, including the low bench over which part of the highway extends. The highest level is 1,300 feet above sea level. Late Pleistocene deposits on these terraces are only slightly tilted, and they truncate, with distinct angular unconformity, all older beds, including lower Pleistocene strata. These relationships clearly indicate that the latest major orogeny occurred here in middle or late Pleistocene time. The Red Mountain thrust fault lies just offshore from Rincon Point, and extends eastward along the north flank of the Ventura anticline (see Map 13).

MAP 17

The sea cliff east of Rincon Point offers a good exposure of the overturned section north of the Rincon fault. North-dipping Monterey (middle Miocene) shale, near the top of the cliff, overlies Santa Margarita (upper Miocene) siltstone that in turn lies on beds of early Pliocene age. Upper Pleistocene deposits of the overlying terrace truncate the older rocks. The large, dark brown, bare area, near the top of the cliff and about one-third of the distance from Rincon Point to Punta

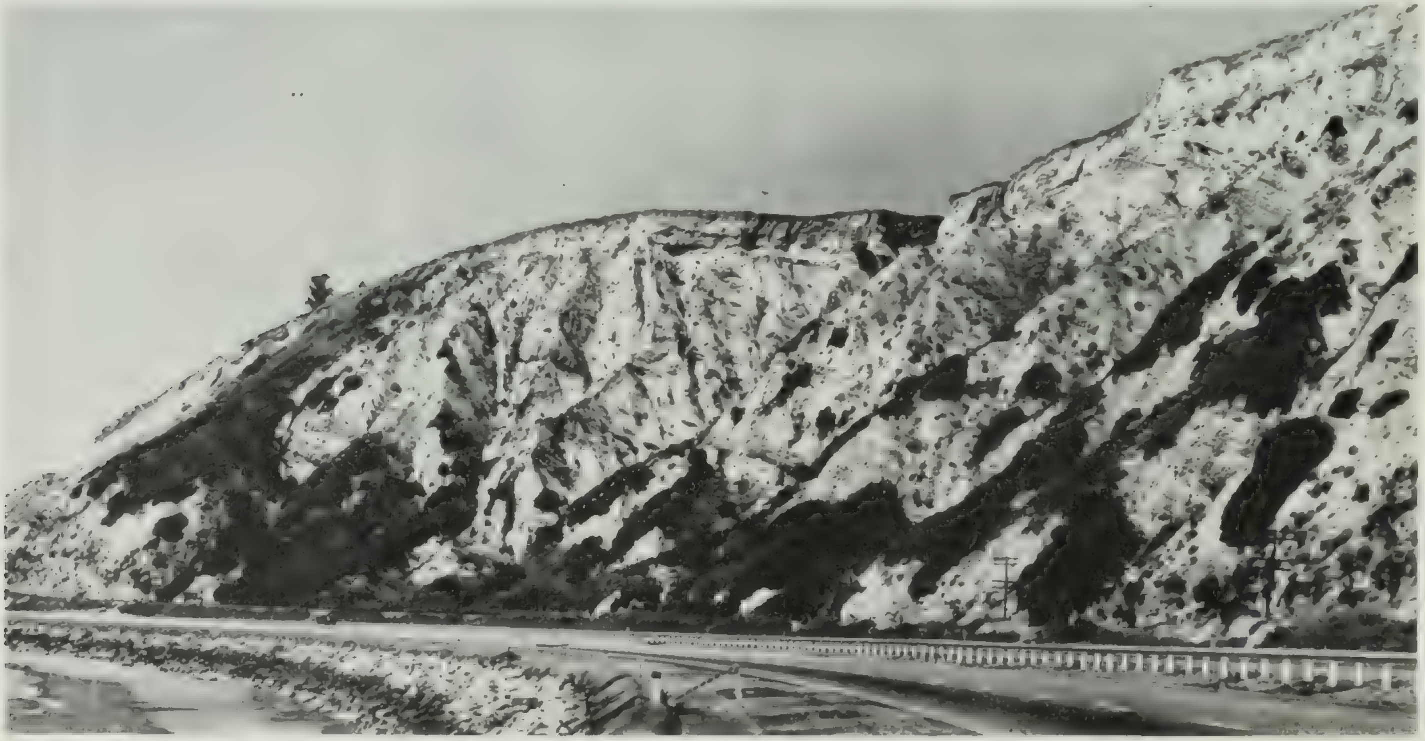


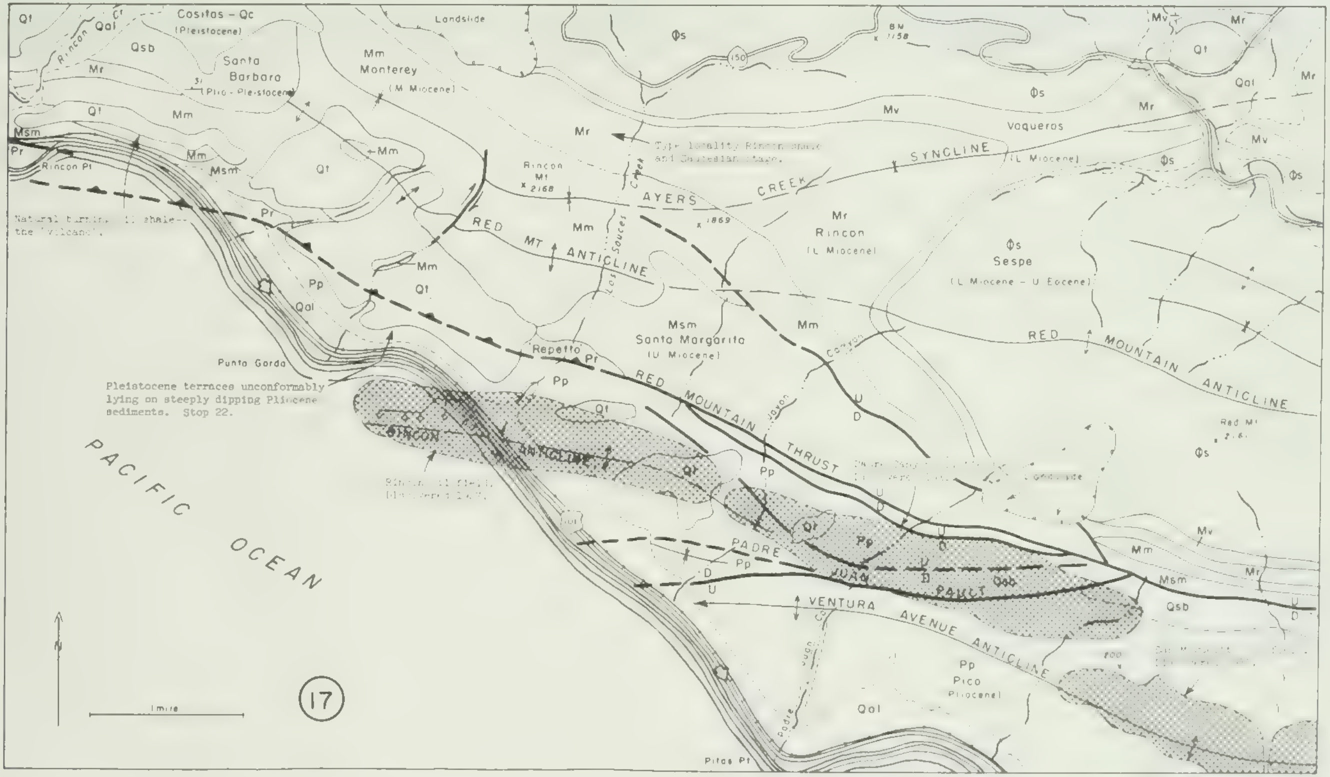
Fig. 24. Angular unconformity between steeply tilted upper Pliocene Pico strata and overlying horizontal Pleistocene terrace deposits. Sea cliff is about 1/4 mile east of Punta Gorda on Coast Highway 101. (Map 17).

Gorda, marks a vent where burning, oil-saturated Miocene shale has scorched the surrounding rock. The pinkish and reddish colors so common in this cliff are the result of burning shale. The vent emits a strong odor of burning oil and sulfur, which can be detected from points near the top of the cliff. At times, and particularly after rains, white smoke or steam rising from this area can be seen from the highway. This vent may have been the site referred to as the 'volcano', which was used as a landmark by early explorers of the California coast. Local residents have long referred to it as such. However, burning tar and oil in the Carpinteria pits may have been the feature observed by the explorers.

At the mouth of the first large ravine in the sea cliff north of Punta Gorda is an exposure of the Red Mountain fault. It is interesting to note that Pliocene beds (especially Pico) are very thick south of the fault, whereas north of the fault very few Pliocene rocks occur and the Pico is absent.

The sea cliff east of Punta Gorda affords a spectacular exposure of the unconformity between a Pleistocene marine terrace deposit and beds of the underlying Pico formation. This exposure records the uplift and intense tilting of upper Pliocene beds, their planation, and the subsequent deposition of terrace material, all in a short interval of time (Stop 22).

The piers in the sea, southeast of Punta Gorda, lie near the axis of the Rincon anticline. Several deflected holes have been drilled from each derrick site on the piers. South of this fold is the south-dipping Padre Juan thrust fault (also known as the Javon, Padre, or Padre Canyon fault), which truncates the Ventura Avenue anticline about one mile north of Pitas



Natural burning oil shale—the 'volcano'.

Pleistocene terraces unconformably lying on steeply dipping Pliocene sediments. Stop 22.

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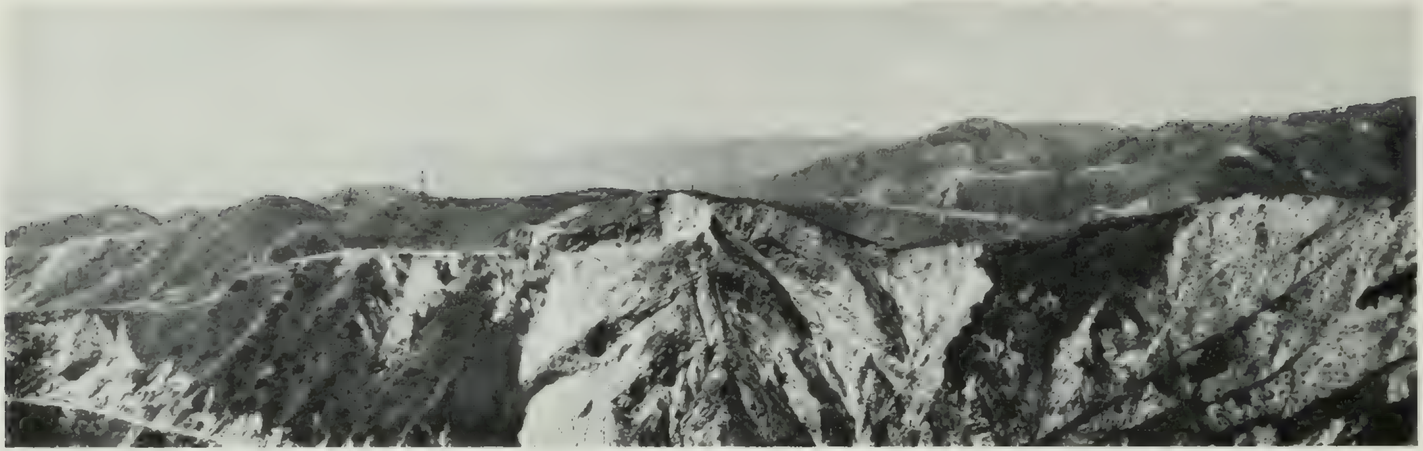


Fig. 25. Crest of Ventura Avenue anticline exposed in the San Miguelito oil field. Strata exposed are upper Pliocene siltstone and sandstone of the Pico formation. View is west towards Santa Barbara. The Santa Ynez Mountains are visible in the distant background. (Map 17).

Point. The block between the Padre Juan thrust and the Red Mountain thrust is a graben.

Type sections at Los Sauces Creek

The banks of Los Sauces Creek offer one of the most complete stratigraphic sections in the area to those who wish to walk up the canyon. Along the sea cliff, beds of the Pico formation form the exposed north flank of the Rincon anticline. These beds have been brought against strata of early Pliocene age (commonly called 'Repetto') along the Red Mountain fault, which here dips 80 degrees northward and has at least 12,000 feet of vertical separation. North of the fault lie shales of the Santa Margarita (upper Miocene) and Monterey (middle Miocene) formations. These strata form the overturned south flank of the complexly faulted and folded Red Mountain anticline. North of the axis of this fold is a tightly folded syncline. On its north flank is the unusually complete and well-exposed type section of the Rincon shale (lower Miocene), a portion of which constitutes the type locality of the Saucesian stage. Basal sandstone of the Vaqueros (lower Miocene) formation and red beds of the Sespe (Oligocene ?) formation occur north of and stratigraphically below the Rincon shale.

Three oil fields lie near the route of travel on Map 17. The Rincon oil field is developed on the Rincon anticline, which lies in the graben bounded by the Red Mountain and Padre Juan thrust faults. More than 38 million barrels of oil has been recovered from Pliocene sands since the discovery of the field in 1927.

The Padre Canyon oil field lies east of the Rincon field on a southeastward-plunging anticline. It also is in the westward-trending graben that contains the Rincon anticline. Closure on the southeast end of the fold is afforded by its plunge and by the Padre Juan fault. Closure on the west is not well understood, but probably is formed by minor cross-faulting in the vicinity of Javon Canyon by a structural terrace, or by both features. Since 1931, more than 7 million barrels of oil have been recovered from sands within the Pico formation.

The San Miguelito oil field is on the Ventura Avenue anticline about 2 miles east of Pitas Point. The topography in the field is very rugged, and points reach an altitude of 1,100 feet only a short distance from the seashore. The Pico strata are deeply eroded, and precipitous V-shaped canyons are common. Because of the very rugged topography, many wells have been directionally drilled. The oil has accumulated in Pliocene strata, owing primarily to anticlinal entrapment. Three zones the First, Second, and Third Grubb, were discovered in 1931, 1944, and 1949, respectively, and more than 31 million barrels of oil has been recovered from them.

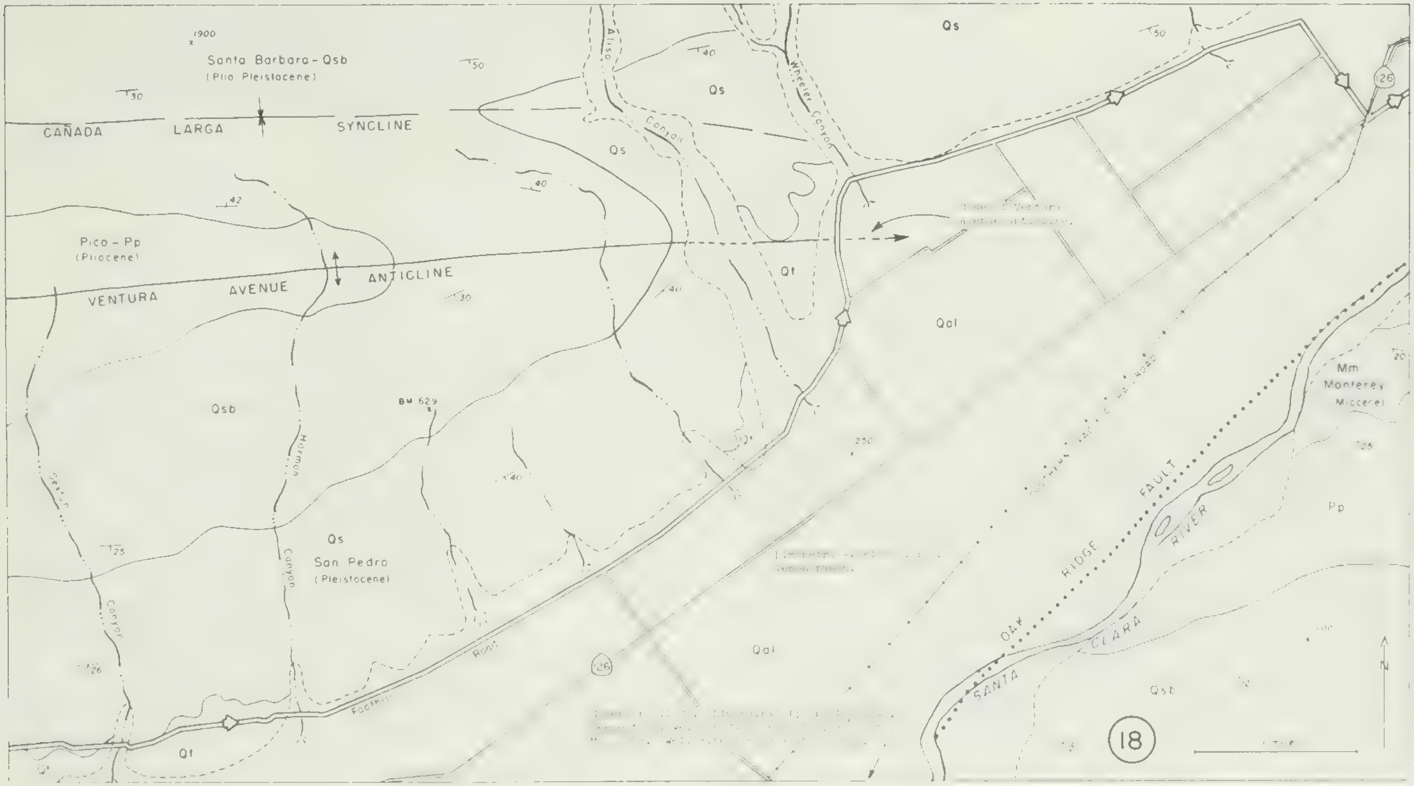
East of the Padre Juan fault, Highway 101, roughly parallels the Ventura Avenue anticline to Ventura (Map 14). Steeply south-dipping Pico (middle and upper Pliocene) shale and sandstone crop out near the axis, and are overlain conformably by the soft clay of the Santa Barbara formation (Pliocene-Pleistocene). Numerous landslides are present in this unit. Eastward from the vicinity of the railroad overpass (see Map 14), boulder conglomerate, sand, and silt of the San Pedro (lower Pleistocene) formation are exposed near the highway.

Of the many marine terraces seen on the slopes between Rincon Creek and the Ventura River, the best developed and preserved are those just west of the Ventura River in an area where five successive terraces are visible.

WESTERN SANTA CLARA RIVER VALLEY

MAP 18

The route of travel continues to the east end of the city of Ventura (along Poli Street, one block north of Main Street), thence eastward along Foothill Road at the base of the hills in back of the city. The route roughly parallels the strike of the Ventura Avenue anticline and skirts the northwestern edge of the Oxnard Plain, which is at least in part a delta plain of the Santa Clara River. Cuts on Foothill Road expose terrace deposits and beds of the San Pedro (lower Pleistocene) formation on the southern flank of the Ventura Avenue anti-



cline. In the Santa Clara River Valley, near the mouth of Wheeler Canyon farther to the east, the road crosses the plunging east end of this anticline.

The broad Santa Clara River Valley is covered mostly by citrus groves, including the Limoneira Ranch which is probably the world's largest lemon ranch. The long rows of tall eucalyptus trees that tower above the citrus groves serve as windbreaks. The wind machines standing upright in the groves are used to circulate air for prevention of frost damage.

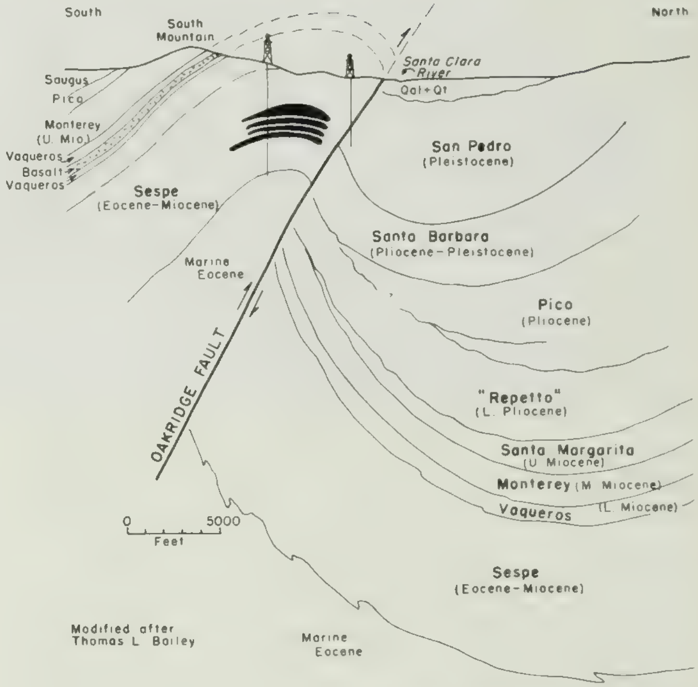
In 1949, the Superior Oil Company drilled an 18,734 foot well on the Limoneira Ranch. At that time, this was the world's deepest well, and it remained the deepest in California until May 1953, when Ohio Oil Company's well 'KCL A' 72-4, in Kern County, exceeded that depth.

MAP 19

At Santa Paula, turn right (south) onto Riverside Drive, cross the Santa Clara River, and proceed eastward following the river road to South Mountain. The oil field on the precipitous slopes of South Mountain, is one of a chain of fields along the Oak Ridge uplift, which is marked by a series of en echelon anticlines. The north flank of the South Mountain anticline is cut by the Oak Ridge thrust fault, here concealed by alluvium, which has brought rocks of Oligocene and Miocene age northward over strata as young as Pleistocene. The road on the north side of South Mountain crosses steeply dipping and overturned red beds of the Sespe formation. Wells here penetrate the thrust fault at depth, and show that it has a dip of 55 degrees or more to the south; the displacement is measurable in thousands of feet.

South Mountain oil field

The South Mountain oil field is picturesque because of the deep erosion that has beautifully exposed the variegated rocks of the Sespe formation. Some of the derrick locations are so inaccessible that drilling equipment had to be transported to them by way of specially constructed inclined railways. The first producing well on South Mountain, completed in April 1916, recovered oil from zones in the Sespe formation. Since then some wells have reached the top of marine sedimentary rocks of Eocene age, and some have pierced the Oak Ridge fault and passed into younger sediments below. This is illustrated in the cross section shown in fig. 26

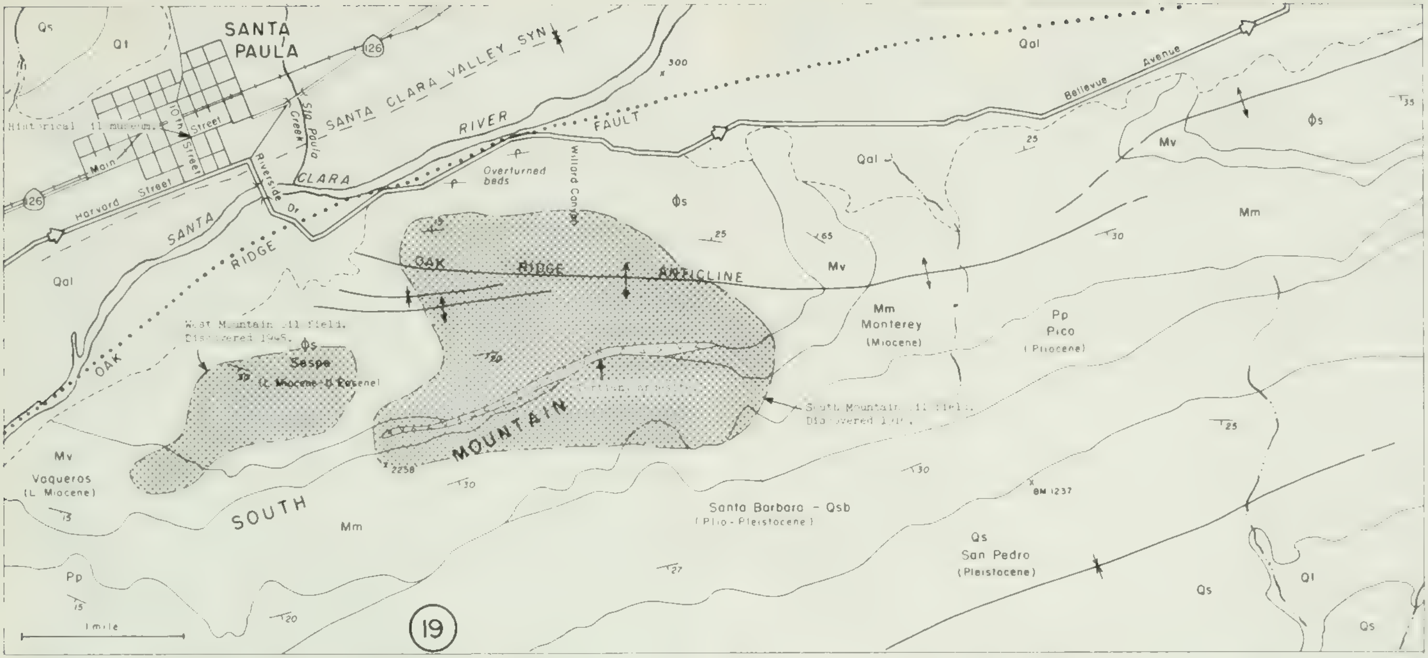


Modified after Thomas L. Bailey

Fig. 26. Cross section through South Mountain oil field.

Origin of oil from Sespe formation

The origin of the oil being produced from these rocks poses a difficult problem. The oil generally is believed to have originated in marine sediments, and to have migrated into nonmarine strata; some geologists, however, believe the oil might be indigenous to the Sespe formation. If the oil migrated from petroliferous marine strata, it may have been derived from the marine shales of Eocene age that underlie the Sespe (mainly Oligocene) formation beneath South Mountain. Some of the oil may have migrated laterally from marine Eocene rocks that lie beneath the Santa Clara syncline (see fig. 26), and some may have migrated upward from Miocene or Pliocene rocks that lie below and on the north side of the Oak Ridge fault. Countless tiny cracks and joints in the shale beds between the source rocks and res-

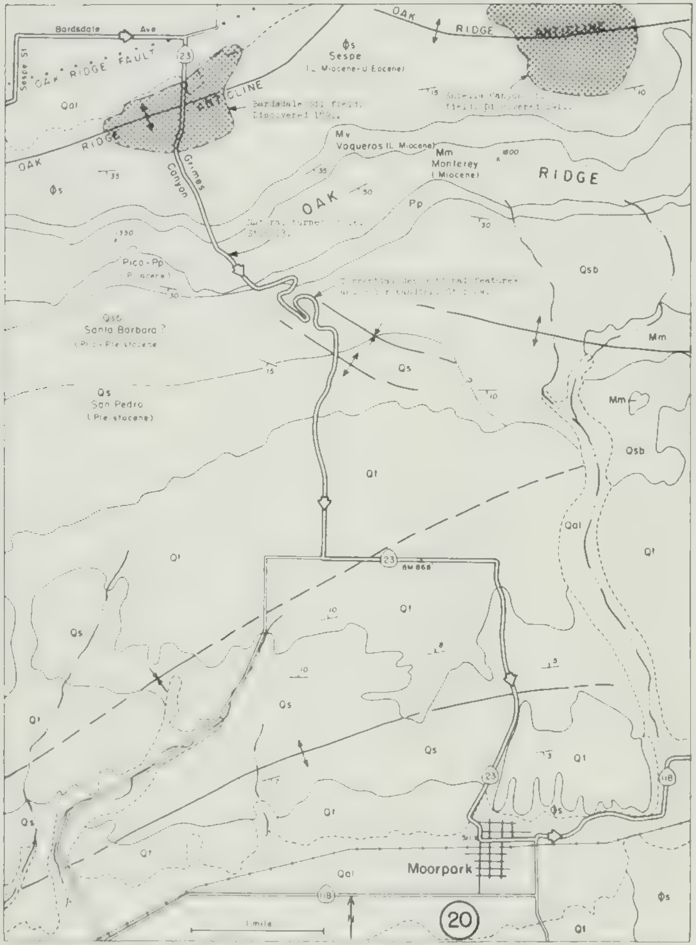


ervoir rock may have acted as channels for upward migration.

On clear days, a side trip to the top of South Mountain affords a magnificent view of the Santa Clara River Valley and the Santa Ynez Mountains. On exceptionally clear days, generally following rainstorms, it is possible to see all four of the Channel Islands and one or two of the Catalina group to the south and west. On the distant skyline to the east, one can see the San Gabriel Mountains dominated by San Antonio Peak, more than 80 miles away. Directly north across the Santa Clara River Valley rises the Santa Paula Ridge, composed of Eocene sedimentary rocks. An extremely thick section of Pliocene rocks is exposed on its lower slopes, and the two units are separated by the San Cayetano thrust, which dips steeply northward. The trace of the fault is clearly shown by differences in rock types in the underlying Pliocene and overlying Eocene rocks, by a break in slope, and by differences in vegetation. The Timber Canyon alluvial fan, directly below the San Cayetano thrust, is clearly observable from this side of the valley.

View from South Mountain

Along the banks of Santa Paula Creek, west of Santa Paula Ridge, lies an intact section, nearly 20,000 feet thick, of Pliocene and Pleistocene rocks. West of the creek is Sulphur Mountain, a long, narrow ridge topped by a flat upland surface and flanked on the south by a steep escarpment. North of Sulphur Mountain and Santa Paula Ridge are the higher Topatopa Mountains, culminating in Hines Peak, elevation 6,700 feet, at the eastern end of the range. Looking to the south, one sees the broad Oxnard Plain and the abruptly terminated western end of the Santa Monica Mountains. In the near foreground rises the Camarillo Hills, which express a gentle anticline on the edge of the Oxnard Plain. The flexure is of very recent origin, for even the Quaternary alluvium is bowed gently on the flanks of this anticline and the strata of the San Pedro formation generally dip parallel to the surface of the hills.



BARDSDALE - SIMI VALLEY - SANTA SUSANA PASS

MAP 20

Bardsdale oil field

From South Mountain the route continues east through the Bardsdale oil field at the mouth of Grimes Canyon. This is another of the anticlinal fields that lie en echelon along the north slopes of Oak Ridge. It is notable for its early discovery (1891) and for a very low rate of decline in production. Some of the oldest wells in this field are still active, or are capable of further production. The original output was obtained solely from the Sespe formation. In 1936, additional production was obtained from marine Eocene strata at depths greater than 5,000 feet. Upper Eocene rocks are several thousand feet thick at depth.

The Grimes Canyon road displays an excellent section of Tertiary and Quaternary rocks that range in age from Oligocene at the mouth of the canyon to Pleistocene at the crest of Oak Ridge. Here the formations are much thinner than in the Santa Clara River Valley to the north. During much of the Tertiary period the area along Oak Ridge was intermittently uplifted, or did not subside as rapidly as the terrain to the north.

The bright red color of part of the Monterey formation, so conspicuous in Grimes Canyon about a mile south of the Bardsdale field, is believed to have been caused by the burning of organic layers within the shale (Stop 23).

Locally the rock has been fused to an obsidian-like material. Until recent years hot gases and smoke issuing from a fissure in Miocene shale on the south slope of South Mountain indicated that the shale was still burning in places. Higher on the grade, the road traverses the Pico (Pliocene) formation, which here is only about 500 feet thick. This formation thickens westward along the strike, and pinches out to the east. The Pico formation is 14,000 feet thick on the north side of the Santa Clara River Valley near Santa Paula Creek, just a few miles from here (Map 10)! Cross-bedded sandstones, stratigraphically above the Pico formation, are exposed still higher on the grade (Stop 24). Here the coarse nature of the sediments, the prominent cross-bedding, and other structural features typical of torrential deposition are very well displayed. A few miles to the west the Santa Barbara formation, of nearly equivalent age, consists mostly of blue-gray silt that

Grimes Canyon

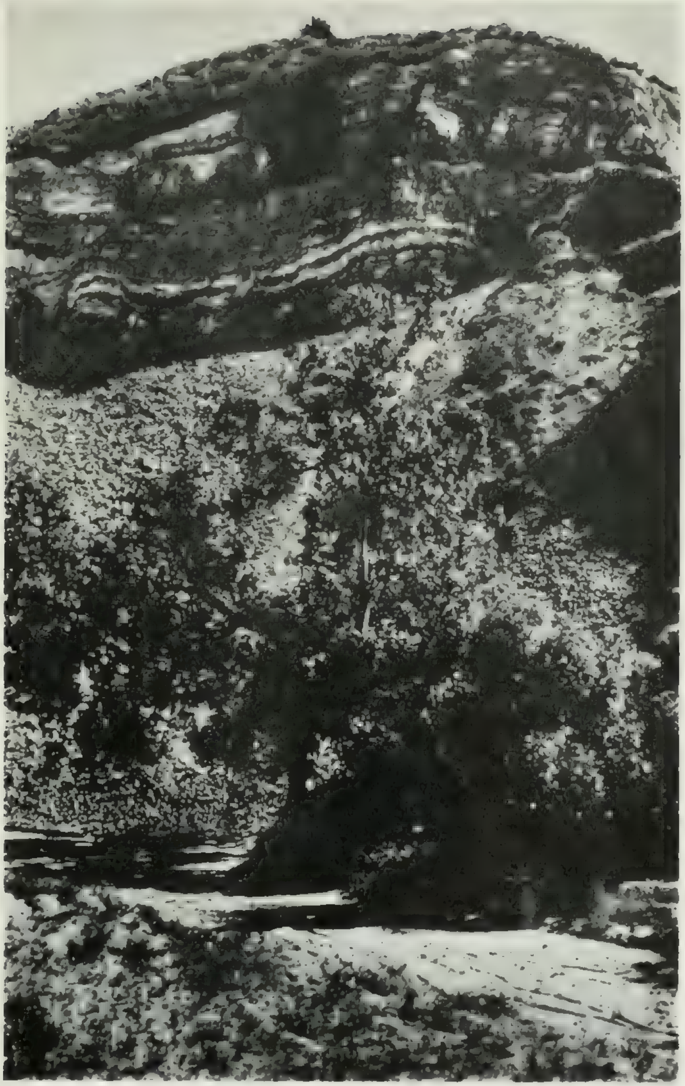


Fig. 27. Natural burned and baked petroliferous shale of the Monterey (Miocene) formation exposed in Grimes Canyon. (Stop 23, Map 20).

grades into the coarse sand and gravel seen here. Such shallow-water features are in marked contrast to the deep-sea, turbidity-flow features shown in the Pliocene sediments at Santa Paula Creek and in the Cretaceous rocks at Santa Susana Pass, San Fernando Valley (Map 23). Note the peculiar, rusty brown color banding in the prominent roadcut on the second hair-pin turn. This banding commonly lies athwart the bedding, and is attributable to the effects of percolating ground waters.

From the top of the grade southeastward to Moorpark the road crosses a broad plain or terrace covered with a deposit of late Pleistocene sand and gravel. Just north of Moorpark the road passes through a canyon cut into loosely consolidated sand and gravel of the San Pedro (Pleistocene) formation. Turn left at Moorpark and proceed eastward into Simi Valley.

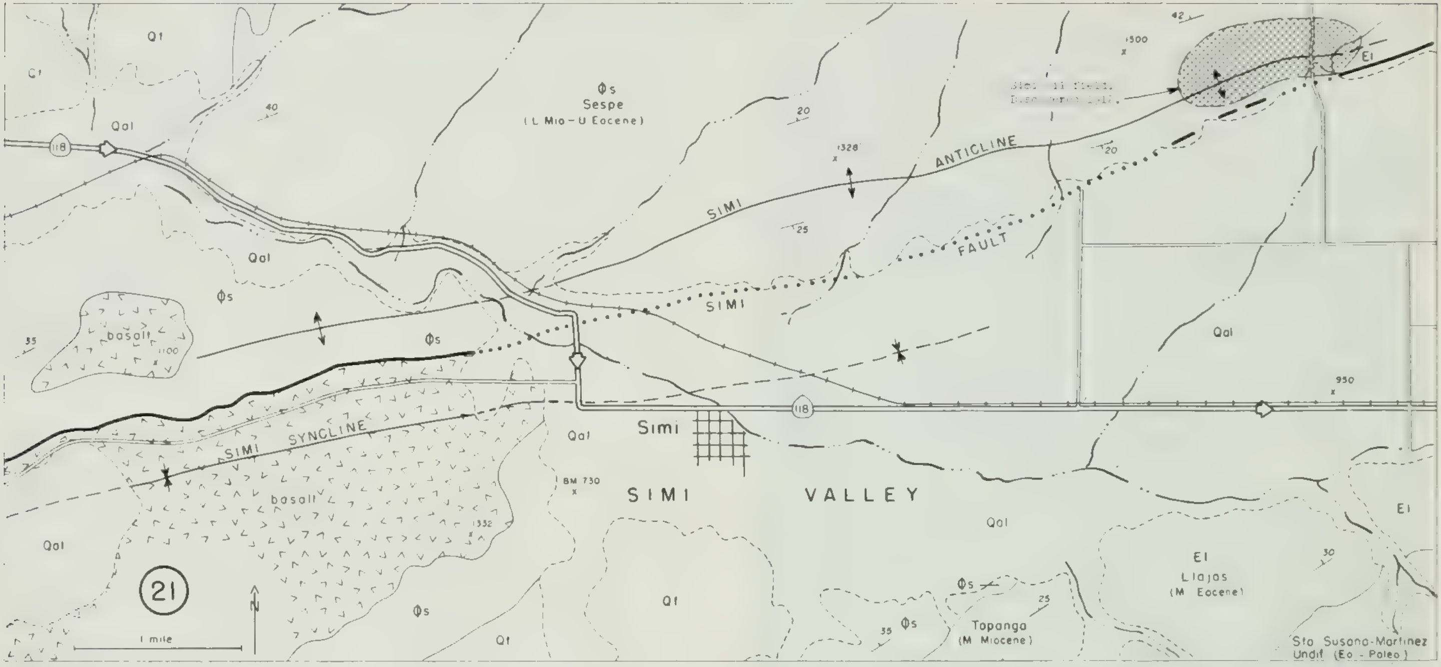
MAP 21

In a steep roadcut, about 3.7 miles east of Moorpark, red and white sandstone and siltstone of the Sespe formation are exposed. The hilltop on the right (south) of the road is capped by a Miocene basalt flow. An even more extensive mass of basalt covers the hill that is just west of the town of Simi.

Simi oil field

The Simi oil field lies on the Simi anticline, which closely parallels the north side of the valley. The axis of this fold crosses the highway about 29 miles northwest of the town of Simi. South of the anticline, and roughly parallel to it, is a prominent fault that follows the foot of the hills. This fault, or others related to it, have modified the structure of the anticline and may have influenced the accumulation of petroleum in the oil field. The oil wells pass through the Sespe red beds near the surface, and most of the production is obtained from the upper part of the underlying Llajas (middle Eocene) formation. The production is small, but the oil, unlike typical California Miocene and Pliocene oils, contains a high percentage of paraffin. Approximately 50 wells are being pumped, and each yields about $2\frac{1}{2}$ barrels per day. The total output of oil from the Simi field is more than $2\frac{1}{2}$ million barrels.

The basal beds of the Sespe formation and the Llajas formation (middle Eocene) are exposed east of the field. This is the area in which the lower part of the Sespe formation has been dated as upper Eocene on the basis of a meagre vertebrate fauna. The Llajas beds are highly fossiliferous.



MAP 22

Continue through Simi Valley toward Santa Susana Pass at the east end of the valley. This valley is a synclinal depression, and formations ranging in age from Cretaceous to Pleistocene are exposed on its margins. At Oil Canyon, on the north side of the valley, active oil seepages occur on outcrops of oil-saturated sandstone.

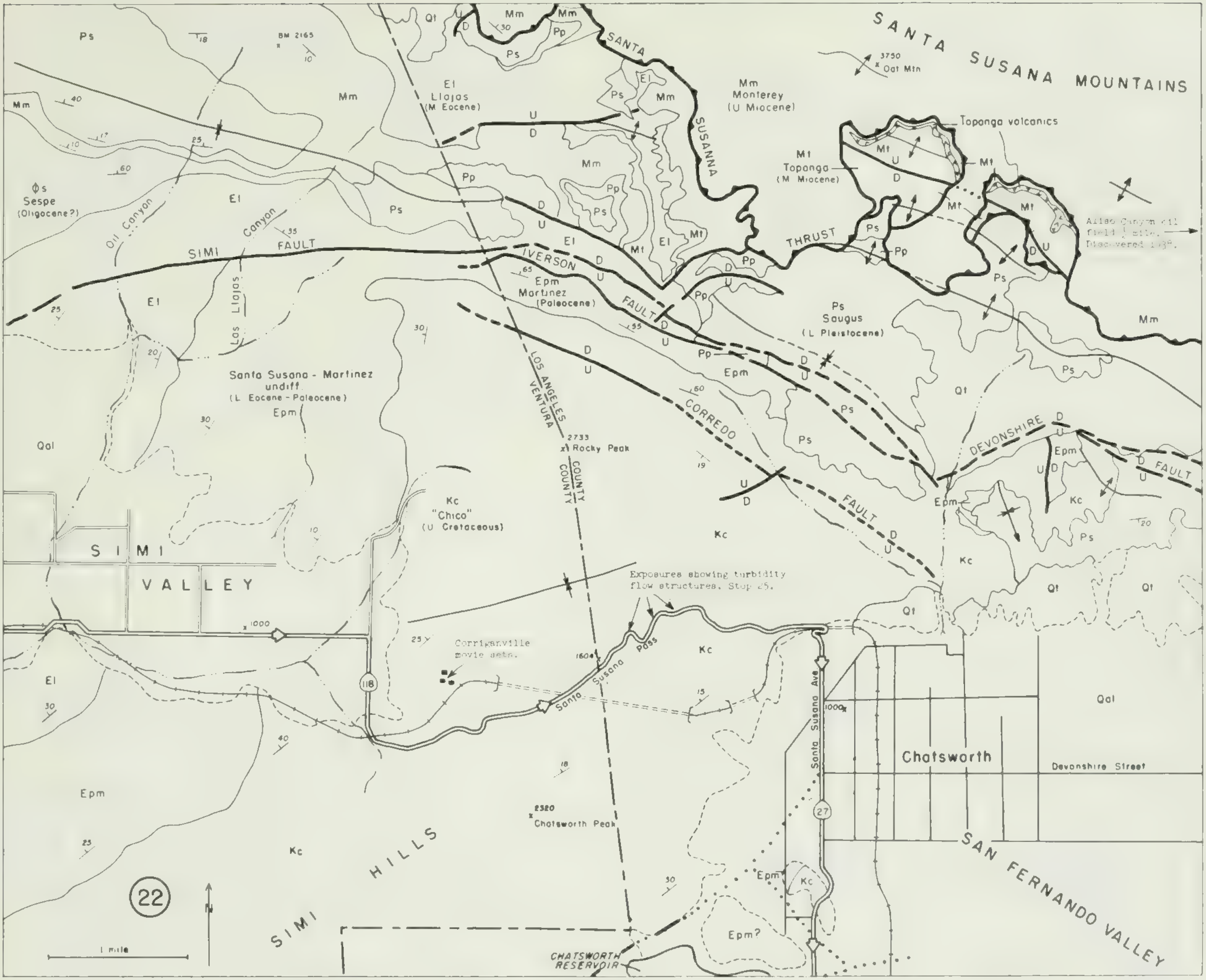
Cretaceous rocks in Santa Susana Pass

At Santa Susana Pass the road traverses a thick section of Cretaceous strata. Cuts east of the top of the grade (Stop 25) provide good exposures of structures, attributable to turbidity flow, that are similar to those in the Pliocene strata at Santa Paula Creek. Here can be seen convolute bedding, pull-aparts, flow clasts, and graded bedding, which are attributable to formation in deep water by submarine landsliding.

Aliso Canyon oil field and Santa Susana thrust

The silver-colored tanks and derricks visible on top of the Santa Susana Mountains to the northeast, and overlooking San Fernando Valley, mark the location of the Aliso Canyon oil field. This field, structurally one of the most complex in California, has oil accumulated in both structural and stratigraphic traps that are contained within a graben concealed beneath the Santa Susana thrust fault. The Santa Susana thrust, one of the most significant faults in these mountains, extends for several miles beyond this area. Because the fault dips gently near the surface, has been recently folded, and is offset locally by tear faults, its trace is very sinuous. The northern block has been thrust southward on the Santa Susana fault for 18 miles along the southern side of the Santa Susana Mountains, and the fault has a minimum vertical displacement estimated to be about 8,000 feet. The fault is nearly flat near the surface, but steepens to almost vertical at depth. It is believed by some geologists to have been steep during its early history and to have later developed a flat segment that roughly followed an erosion surface. It was active as recently as Pleistocene time, as terrace deposits of that age are overridden by the thrust.

Another feature that demonstrates the recency of deformation in this area can be seen from Stop 25. This is a Pleistocene terrace deposit that is visible along the south flank of


SANTA SUSANA MOUNTAINS
3750 Oat Mtn
BM 2165
Mm Monterey (U Miocene)
El Llajas (M Eocene)
Mt Topanga (M Miocene)
Topanga volcanics
ɸs Sespe (Oligocene?)
Oil Canyon
Canyon
Los Llajas
SIMI FAULT
SANTA SUSANA THRUST
IVERSON FAULT
Epm Martinez (Paleocene)
Ps Saugus (L Pleistocene)
Santa Susana - Martinez undiff. (L Eocene - Paleocene)
LOS ANGELES COUNTY
VENTURA COUNTY
2733 Rocky Peak
CORREDO FAULT
DEVONSHIRE FAULT
Kc "Chico" (U Cretaceous)
Aliso Canyon oil field ½ mile. Discovered 1938.
SIMI VALLEY
Exposures showing turbidity flow structures. Stop 25.
Corriganville movie sets.
Santa Susana Pass
118
27
Santa Susana Ave
Chatsworth
Devonshire Street
Qal
Qt
Pp
2320 Chatsworth Peak
SIMI HILLS
SAN FERNANDO VALLEY
CHATSWORTH RESERVOIR
22
N
1 mile

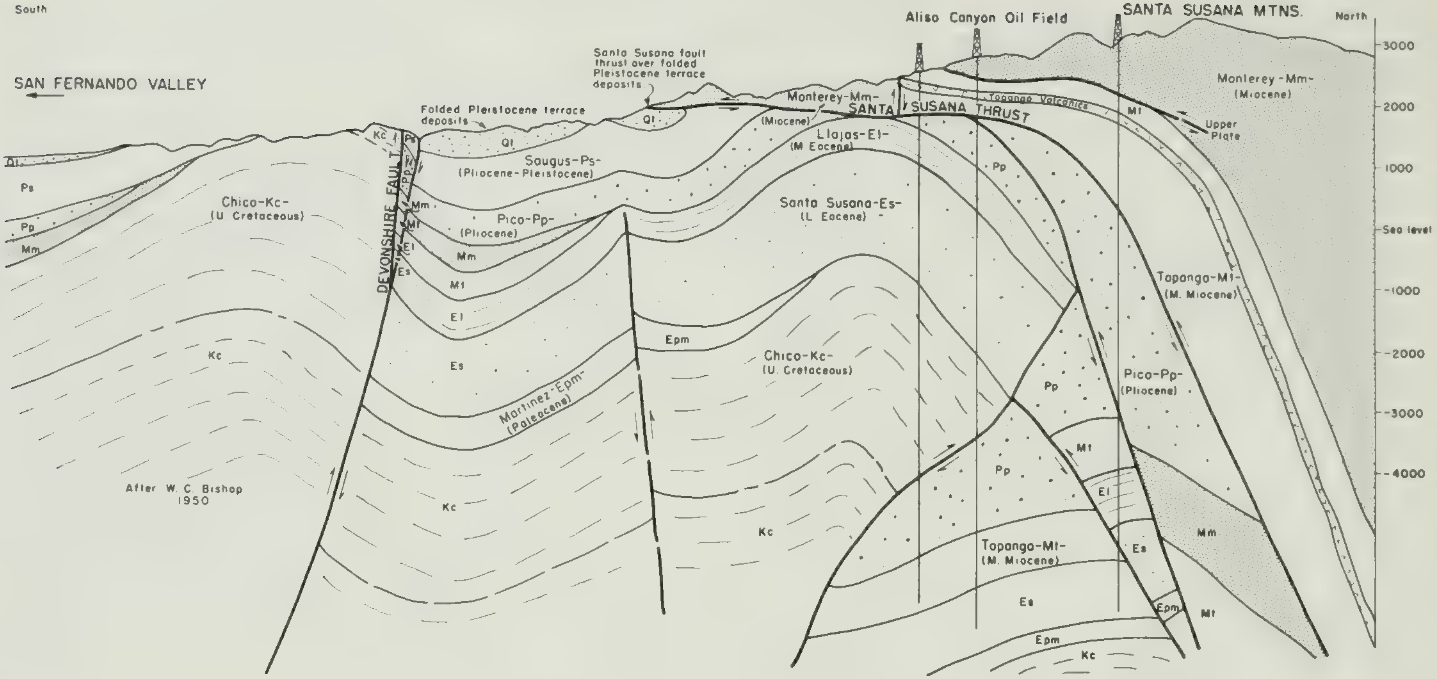


Fig. 28. Cross section through Aliso Canyon oil field.

the Santa Susana Mountains at a distance of several miles due east. Faulting along the north edge of the valley has caused this terrace deposit to be tilted about 15 degrees northward, toward the mountains from which the sediments were derived.

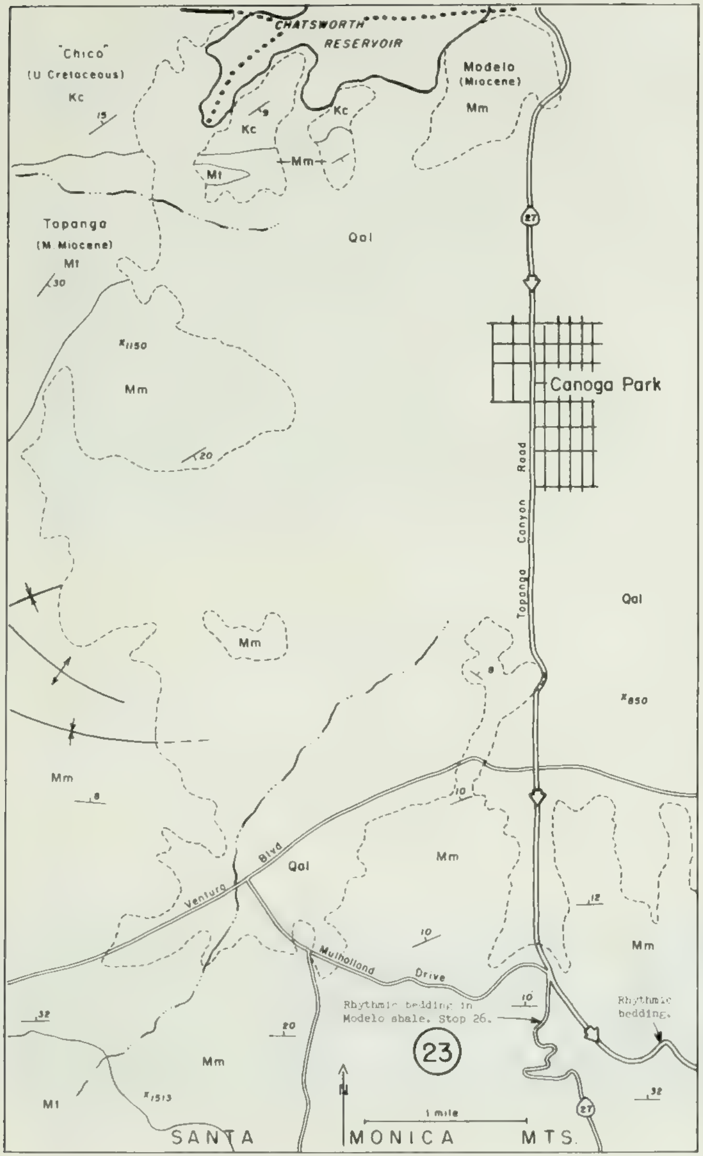
The rocks exposed in the Santa Susana Mountains, ranging in age from Cretaceous through Pleistocene, are shown in the following generalized columnar section:

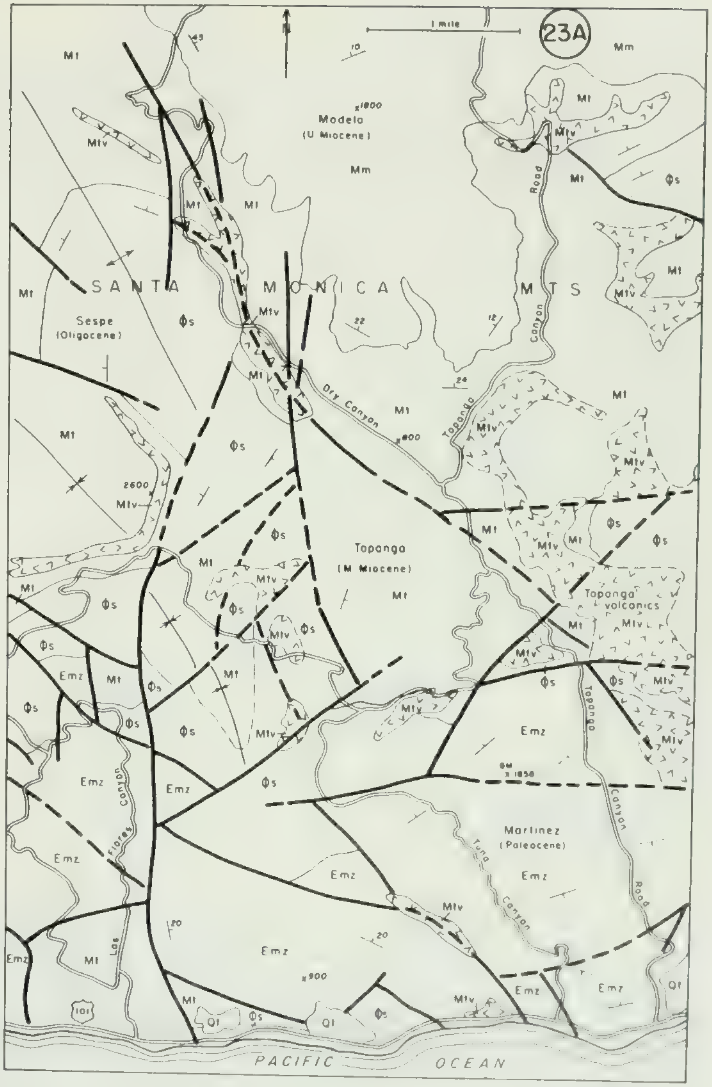
Terrace deposits (nonmarine upper Pleistocene)
Saugus (nonmarine Plio-Pleistocene)
Pico (marine upper and lower Pliocene)
Monterey (marine upper and middle Miocene)
Topanga (marine middle Miocene)
Llajas (marine middle Eocene)
Santa Susana (marine lower Eocene)
Martinez (marine Paleocene)
Chico (marine Upper Cretaceous)

MAP 23 and MAP 23A

From Santa Susana Pass the route turns southward across the western margin of San Fernando Valley via Topanga Canyon Road to the intersection with Mulholland Drive, in the foothills of the Santa Monica Mountains.

The prominent hills west of Chatsworth are composed of northwest-dipping Upper Cretaceous sandstone and shale. They are unconformably overlain by Martinez (?) beds (Paleocene). Middle and upper Miocene sedimentary rocks, consisting of well-bedded marine sandstone, conglomerate, and shale, are exposed in a shallow west-trending syncline that plunges eastward beneath the alluvium of San Fernando Valley.


CHATSWORTH RESERVOIR
"Chico" (U Cretaceous)
Kc
Modelo (Miocene)
Mm
Mt
Topanga (M Miocene)
Mt
Qal
27
Canoga Park
Topanga Canyon Road
x1150
x850
Ventura Blvd
Mulholland Drive
Rhythmic bedding in Modelo shale. Stop 26.
Rhythmic bedding.
23
x1513
1 mile
N
SANTA MONICA MTS.


23A
1 mile
N
Mt
Mm
Modelo (U Miocene)
x1800
Mtv
SANTA MONICA MTS
Sespe (Oligocene)
Φs
Dry Canyon
Topanga Canyon Road
x800
2600
Topanga (M Miocene)
Topanga volcanics
Emz
Martinez (Paleocene)
Flores Canyon
Los
Tuna Canyon
x1850
x900
101
Qt
PACIFIC OCEAN

SANTA MONICA MOUNTAINS - CAHUENGA PASS

The Santa Monica Mountains, a low but rugged range that bounds the Los Angeles basin on the north, extend westward 50 miles from the Los Angeles River to the sea. The range is structurally complex, although its eastern part is mainly a westward plunging anticline. Modelo (upper Miocene) sandstone and shale dip away from the crest of the mountains on both flanks of the fold, and older, more highly deformed rocks are exposed along its axis. The oldest rocks are metamorphosed sediments (phyllites and argillites) of the Santa Monica (Triassic ?) formation. These have been intruded by granite and granodiorite, probably during the Jurassic or Cretaceous time. Cretaceous and Paleocene rocks consisting of marine and nonmarine conglomerate and marine sandstone and shale, overlie the older rocks with steep angular unconformity. Sespe (mainly Oligocene) red beds and Topanga (middle Miocene) sandstone, conglomerate, and volcanic flows and sills are generally more concordant with the underlying rocks. Shale of the Modelo (upper Miocene) formation is the youngest stratified sedimentary rock exposed on Mulholland Drive.

Rhythmic bedding in Modelo shale

On a short sidetrip to a roadcut on the east side of Topanga Canyon Road (Stop 26), 0.4 mile south of Mulholland Drive, one can see an excellent exposure of rhythmic bedding within the Modelo formation. Most apparent is the alternation of dominantly dark and dominantly light zones of finely stratified beds (see photo). These zones are composed of beds, an inch thick, of light-colored sandstone and siltstone interlayered with beds of dark-colored organic material, composed mostly of diatom tests. These layers represent rhythmic deposition of the two types of material. Careful study shows that each in turn is composed of minute laminae of alternating light and dark color. Such rhythmic bedding may represent climatic oscillations that affected the type of deposition.

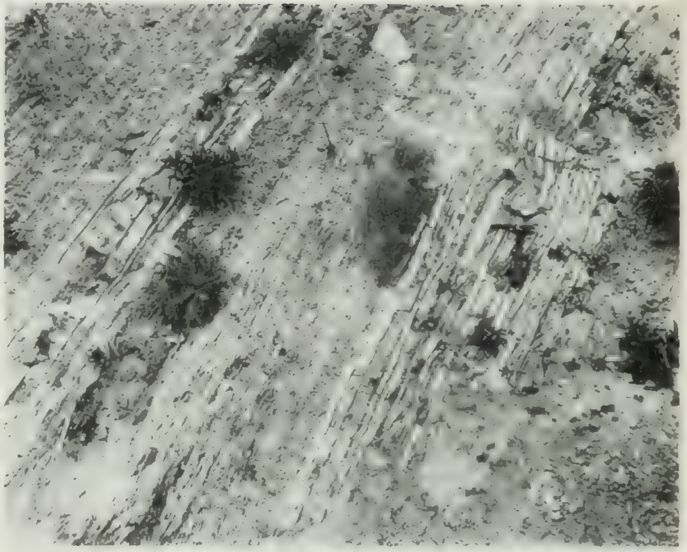


Fig. 29. Rhythmic-bedded siliceous shales of the Modelo (Miocene) formation at Topanga Canyon Road in the Santa Monica Mountains. Note sandstone dikes crossing the bedding planes of the shale. (Stop 26, Map 23).

At Stop 26 sandstone dikes can be seen crossing the bedding planes of the siliceous shale. These probably were formed by the squeezing of sand or poorly consolidated sandstone upward along joints and bedding planes in the shale.

East of Topanga Canyon Road, along Mulholland Drive, beds of the Modelo formation are exposed for a distance of 4

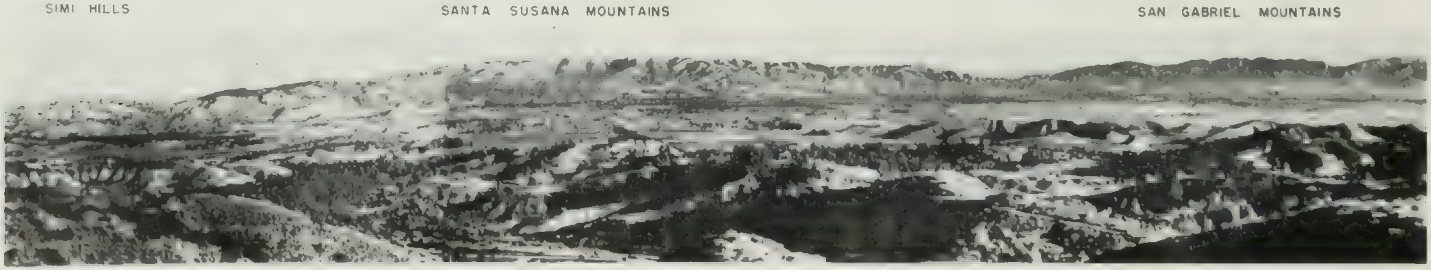


Fig. 30. View north across San Fernando Valley from Topanga Canyon Road. Rocks in foreground are Modelo shales (upper Miocene). Cretaceous strata in Simi Hills form prominent cliffs. (Map 23).

miles. This formation is composed of fossiliferous, cherty, siliceous shale, punky diatomaceous shale, gray and brown sandstone, and soft, earthy shale. Grit, sandstone, conglomerate, and phosphatic oolite occur as basal members of the formation in this region. The Modelo formation commonly dips gently to the north and rests unconformably upon several older rock formations that form most of the Santa Monica Mountains. Locally, the beds have been crumpled by soil creep and small landslides. Many points along Mulholland Drive provide panoramic views of the San Fernando Valley and of the San Gabriel Mountains, Verdugo Mountains, Simi Hills, and Santa Susana Mountains, which border the valley on the north and west.

Mulholland Drive

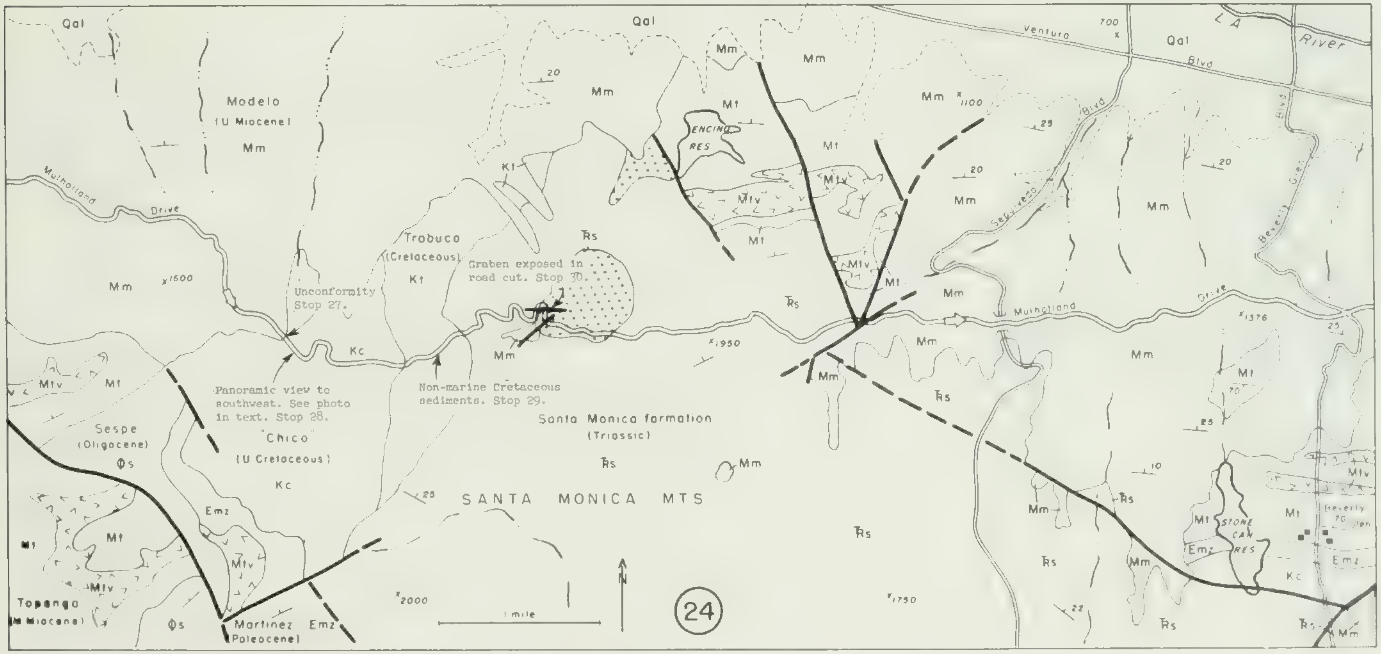
Map 23A is provided for those who wish to travel south across the Santa Monica Mountains via Topanga Canyon Road to Highway 101 on the coast. Complexly faulted and folded Tertiary sedimentary and volcanic rocks are well exposed in the steep canyon walls.

MAP 24

Brown conglomerates of the Chico (Upper Cretaceous) formation are overlain unconformably by massive Modelo sandstone in the roadcut at Stop 27. Here the oldest unmetamorphosed marine sedimentary unit in the Santa Monica Mountains is overlain by one of the youngest formations in these mountains. The conglomerate is typical of the rock that forms about three-quarters of the Upper Cretaceous marine sediments in this part of the range. It is composed of rounded cobbles of varicolored quartzite, dense porphyritic granite, and basalt, chips of black slate, and a matrix of micaceous sandstone with a distinctive greenish brown tinge. To the south, the Chico conglomerate is overlain, apparently conformably, by fossiliferous Paleocene (or lower Eocene) shale and algal limestone of the Martinez (?) formation. The Modelo formation (upper Miocene) overlaps all of these older sedimentary formations with pronounced angular discordance.

Chico conglomerate

Much of the surface structure shown on the north half of Map 23A can be seen from Stop 28. See the labeled photograph as an aid for identifying the surface exposures.



Unconformity Stop 27.

Graben exposed in road cut. Stop 30.

Panoramic view to southwest. See photo in text. Stop 28.

Non-marine Cretaceous sediments. Stop 29.

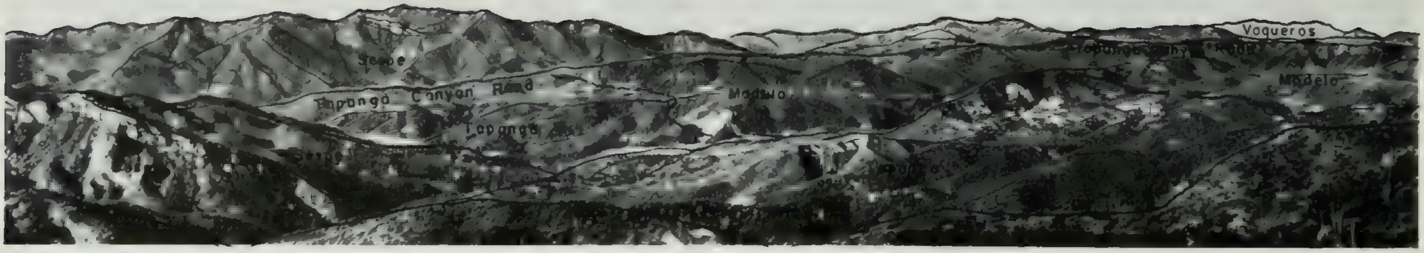


Fig. 31. Panoramic view west along crest of the Santa Monica Mountains from Stop 28, Map 24, on Mulholland Drive.

Stop 29 is a short distance east of the approximate contact between marine Upper Cretaceous rocks to the west and nonmarine Upper Cretaceous rocks to the east. The nonmarine red conglomerate has a soft, clayey sandstone matrix, and contains cobbles similar in composition but more highly polished than those in the marine member. Although the contact is poorly exposed, the nonmarine conglomerate is believed to rest with depositional contact upon the Santa Monica formation (Triassic ?) to the east, and to grade upward into the overlying indurated brown marine conglomerate.

The Santa Monica formation (Triassic ?), which covers nearly one-fourth of the total area of the eastern part of the Santa Monica Mountains, is exposed for about 2½ miles east of Stop 29. It consists mostly of hard, dark gray and bluish gray to black argillite that is fairly uniform in lithology. It also contains light gray siltstone, quartzitic sandstone, and slate. The slate has a well developed cleavage which generally is parallel to the original bedding. At or near intrusive contacts with Jurassic (?) granitic rock the argillite has been metamorphosed to spotted slate, dark gray phyllite, and mica schist.

The granitic rocks, exposed in the road cut at Stop 30, include light gray biotite granite, dark gray diorite, and are so highly disintegrated that they crop out as soft masses and resemble a coarse friable sandstone. The rock is quarried locally for road fill and related products. See figure 32 for details of faulting at this site.

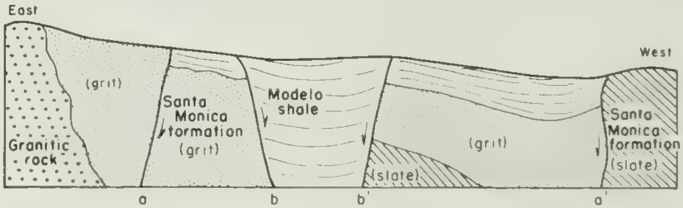


Fig. 32. Diagrammatic sketch of faulting in roadcut on Mulholland Drive at Stop 30. The blocks of the Modelo formation between faults a and a' have moved downward relative to the adjacent rocks, and the block between faults b and b' has been dropped farther.

The following paragraphs pertaining to Map 24 and Map 25 are intended as brief summaries of the geology along the main roads that generally are used to return to the metropolitan areas from Mulholland Drive. Roads to the north provide access into San Fernando Valley, and roads to the south provide access to Santa Monica, Westwood, and Hollywood.

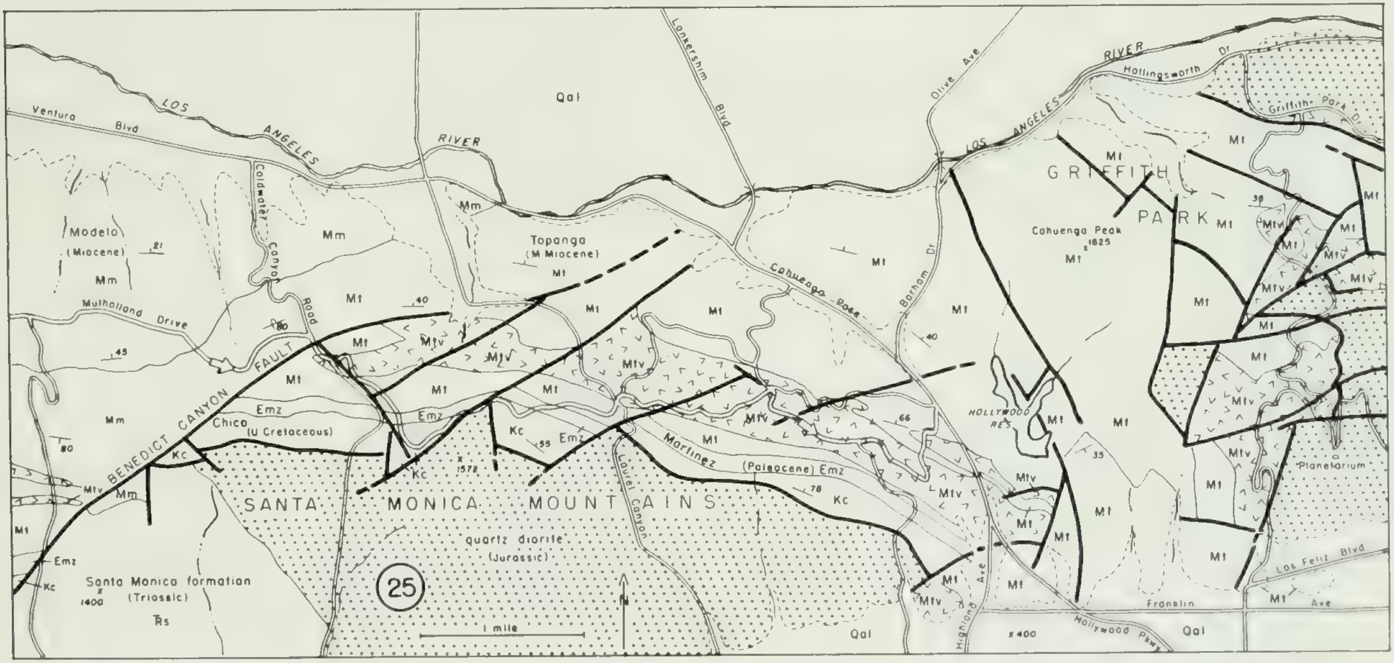
Sepulveda and Beverly Glen Boulevards, north: Both Sepulveda and Beverly Glen Boulevards cut through north-dipping sandstone and siliceous shale of the lower part of the Modelo formation. The white, diatomaceous shale of the upper part of the Modelo formation easily can be distinguished from the tan siliceous shale and sandstone of the lower part of the formation, both by color differences and hardness.

Sepulveda Boulevard, south: Beneath the Modelo formation is a thick section of spotted slate and phyllite of the Santa Monica formation. Approximately 2 miles south of the tunnel at the crest of the mountains, the axis of the Santa Monica anticline is crossed, but confirming dips in the strata are not visible from the road. Slate on the south slopes of the mountains is unconformably overlain by south-dipping Modelo sandstone (south of Map 24), and conglomerate of the Topanga (middle Miocene) formation is faulted against Modelo sandstone near the base of the mountains.

Beverly Glen Boulevard, south: Marine beds of the Modelo formation, consisting of alternating sandstone and siliceous shale, are exposed for nearly a mile south of the junction of Beverly Glen Boulevard with Mulholland Drive. Massive conglomerate and sandstone of the Topanga formation, dipping steeply to the north, underlie the Modelo formation and are exposed as far as the southern edge of the village of Beverly Glen. Small intrusive bodies of diabase, abundant in the middle of the Topanga formation, are well exposed just north of the village. Southward, the boulevard crosses a narrow band of Paleocene and Cretaceous rocks and then a thick section of Santa Monica slate (Triassic ?).

MAP 25

Coldwater and Laurel Canyons, north: Both Coldwater and Laurel Canyons offer good exposures of north-dipping members of the Topanga formation, in which intrusive sills and dikes of diabase are present. These rocks are overlain by the Modelo formation near the foot of the mountains.



Coldwater and Laurel Canyons, south: The Coldwater and Laurel Canyon roads traverse the largest expanse of granite and granodiorite in the eastern Santa Monica Mountains. Volcanic agglomerate in the Topanga formation can be seen near the intersection of Mulholland Drive and Laurel Canyon Road.

Mulholland Drive to Cahuenga Pass: Near the west edge of Map 25 Mulholland Drive trends approximately parallel to the strike of the siliceous shale and massive sandstone of the Modelo formation. The remainder of the route passes through a thick section of the Topanga formation in which sills of diabase are present. Pillow structure exists locally within the diabase, and volcanic agglomerates are interbedded with the Topanga sandstone.

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

GEOLOGIC GUIDE NO. 3

LOS ANGELES BASIN

1954

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO

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OLAF P. JENKINS, *Chief*

San Francisco
Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

GEOLOGIC GUIDE NO. 3

LOS ANGELES BASIN

By BENNIE W. TROXEL

GEOLOGIC GUIDE FOR THE LOS ANGELES BASIN, SOUTHERN CALIFORNIA

By Bennie W. Troxel *

INTRODUCTION

General Statement. The term "Los Angeles basin" is applied in a geographic sense to the lowland area now occupied by Los Angeles and neighboring cities. This lowland is about 50 miles long in a northwest direction and about 20 miles wide. It is bounded on the north by the Santa Monica Mountains, on the northeast by the Repetto and Puente Hills, on the east and southeast by the Santa Ana Mountains and the San Joaquin Hills, and on the south, southwest, and west by the Palos Verdes Hills and the Pacific Ocean (fig. 1). Downtown Los Angeles is at the northern margin of the basin, and Santa Monica and Newport Beach are near its northwest and southeast coastal margins, respectively.

The term "Los Angeles basin" is applied in a purely geologic sense to the site of a former marine embayment that existed as early as mid-Miocene time, when the encroachment of the sea apparently was most extensive. This sea extended inland as far as Pasadena and Pomona, covered the present lowland area and most of the area now occupied by the hills that surround this lowland, and was connected with another sea that occupied the Ventura basin to the northwest. Marine sediments were laid down in the Los Angeles basin during most of subsequent Tertiary time, and in some parts of the basin during Pleistocene time. In this geologic guide the Los Angeles basin is referred to in a geologic sense.

The route indicated on figure 1 is approximately 210 miles long, and is confined mainly to the marginal areas of the basin. Accumulative mileage from the starting point at the Los Angeles Civic Center is indicated in brackets both on the strip maps and in the descriptive text.

The general trend of the tour is eastward from downtown Los Angeles through the Repetto and Puente Hills to Pomona, thence southward along the Santa Ana Mountains to Laguna Beach, northwestward along the Pacific coast to the Palos Verdes Hills, and northward to Los Angeles.

Two days are recommended for the tour. The route from San Pedro around the south and west slopes of the Palos Verdes Hills and through the Baldwin Hills can be readily followed as a separate trip if desired.

Acknowledgments. This geologic guide was prepared under the direction of A. O. Woodford, who suggested the route of travel and provided the writer with many of the data contained herein. Geological data also were kindly furnished by J. E. Schoellhamer, J. G. Vedder, and R. F. Yerkes. The writer was accompanied in the field by Woodford on the Montebello to Pomona segment of the route, and by Schoellhamer and Vedder on the Pomona to Newport Beach segment. The writer also is grateful for helpful criticism by A. O. Woodford, L. A. Wright, and R. H. Jahns.

The strip maps are reproductions of parts of a large geologic map that accompanies a report on the geology of the Los Angeles basin elsewhere in this volume (Woodford, Schoellhamer, Vedder, and Yerkes, Contribution No. 5, Chapter II). Numerous other publications, particularly U. S. Geological Survey Professional Paper 207 and California Division of Mines Bulletin 118, were used as sources of information.

Stratigraphic Features. Marine Pliocene and Quaternary sedimentary rocks have a known thickness of at least 10,000 feet in the central part of the Los Angeles basin. During Pliocene and Pleistocene time the basin became progressively shallower and smaller, and foraminiferal studies indicate that the depth of the sea gradually decreased from more than 4,000 feet to about 900 feet in the interval from early to late Pliocene time (Natland, 1952, p. 50). Marine Pleistocene strata were restricted principally to the coastal margin and adjacent parts of the basin, and they grade northward and eastward into continental sediments. From 50 to 200 feet of lower Pleistocene marine strata overlie upper Pliocene strata in the West Coyote area of the Coyote Hills.

Although the late Tertiary Los Angeles basin probably took form in middle Miocene time, parts of the area it occupies received sediments during earlier Tertiary and also during late Cretaceous time. This is shown by the existence of Upper Cretaceous and Paleocene marine strata in the Santa Ana and Santa Monica Mountains, Eocene marine strata in the Santa Ana Mountains, and Oligocene (?) continental strata and lower Miocene marine strata in the Santa Ana Mountains, San Joaquin Hills, and Santa Monica Mountains.

The Upper Cretaceous, Tertiary, and Quaternary cover was deposited on a basement of metamorphic and igneous rocks. The Catalina schist and associated rocks (Jurassic ?) underlie the southwestern part of the basin, and are exposed in the Palos Verdes Hills. Pre-Cretaceous metasedimentary rocks, in part of Triassic age, are exposed in the Santa Ana Mountains southeast of the basin, and in the Santa Monica Mountains northwest of the basin. These metasedi-

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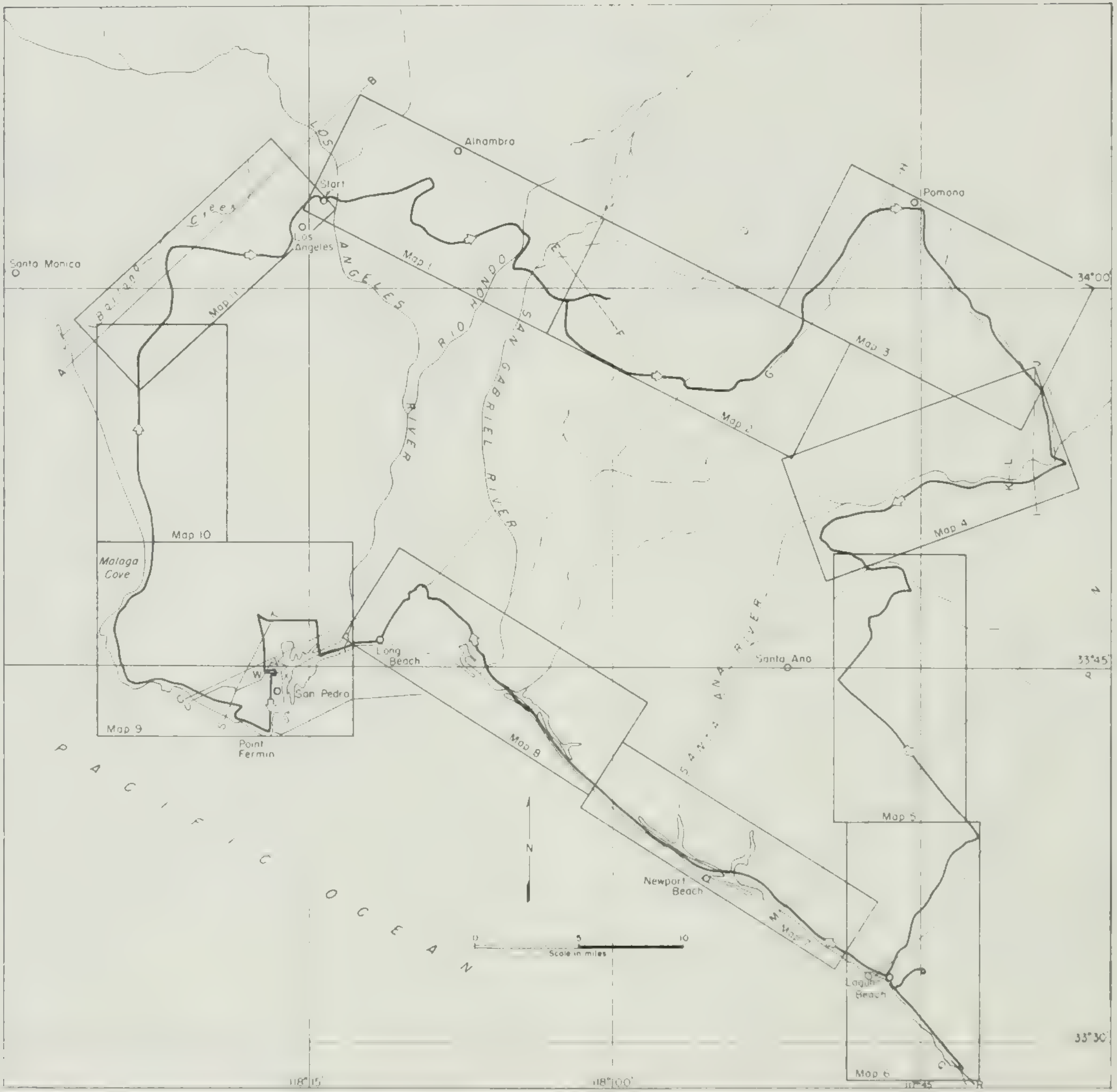


FIGURE 1. Index map of the Los Angeles basin and its margins, showing the locations of strip maps, structure sections, principal streams, and the general route of travel represented by the roadlog.

*Table 1. Principal geologic formations in the Los Angeles basin, California.**

System	Series	Stage	Unit (name)	Map symbol	Thickness (ft.)	General character and distinctive features	Known distribution	Remarks
QUATERNARY	Recent		Alluvium	Qal	0 to 1,000	Unconsolidated, poorly sorted sand, gravel, and silt.	Extensive throughout low areas of Los Angeles basin; in stream channels.	Source of sand and gravel for aggregate; clay for brick. Important as water reservoir and subsurface channelways.
			Sand dunes	Qs		Unconsolidated, well-sorted, rounded grains, chiefly quartz.	Common along coast between Palos Verdes and Playa Del Rey.	
	Pleistocene	Upper	Continental sediments (various names)	QPu		Reddish alluvium. Similar to recent alluvium but commonly more eroded.	Generally inland from shoreline.	Probably contemporaneous with lowest horizontal coastal marine terrace deposits.
			Palos Verdes sand		0–15	Marine, fossiliferous, coarse-grained sand and gravel, including some silty sand and silt.	On lowermost terrace in Palos Verdes Hills. Marine deposits in San Joaquin Hills and on summits of the Costa Mesa, Huntington Beach and other mesas may be contemporaneous.	Commonly grade inland into continental sediments.
		Lower	San Pedro sand	QPl	300—	Evenly bedded to cross-bedded sand; some subordinate gravel, silty sand, and silt.	Extensively exposed along north and east flanks of Palos Verdes Hills.	Sands are composed chiefly of granitic debris. Indicates that material was transported from north across Los Angeles basin and the filled deep basin of Lomita time.
			Timms Point silt		120—	Greenish-gray, generally massive, sandy silt and silty sand.	Vicinity of San Pedro—very limited.	
			Lomita marl		100—	Principally marl and calcareous sand. Calcareous sand is composed mainly of fragments of calcareous organic remains; inorganic grains from Monterey formation.	North and east flanks of Palos Verdes Hills.	Probably an offshore reef deposit marking the position of an ancient submarine ridge that antedated the present Palos Verdes Hills.
TERTIARY	Pliocene	Upper and middle	"Pico" formation	TQ	4,000 ±	Chiefly greenish-gray micaceous siltstone and fine to coarse light gray feldspathic sandstone. Pebble conglomerates and fine rubble breccias locally present, becoming more numerous near top of the Pliocene section.	Thickest in central deep of Los Angeles basin. Numerous exposures in hills surrounding present lowland surface of the basin.	Undifferentiated from lower Pliocene sediments encountered in wells except by foraminiferal faunas; some lithologic variation in strata exposed in surrounding hills where near-shore deposition occurred. Type locality is in Ventura basin.
		Lower	Repetto formation	Tr	5,000—?	Mostly siltstone with a few thin layers of sandstone and conglomerate, locally containing fragmental remains of shallow-water mollusca.	Thickest in central deep of the Los Angeles basin. Extensively exposed in hills surrounding the present lowland.	Principal source of petroleum in the Los Angeles basin. Foraminiferal faunas indicate that sediments of early Pliocene age were deposited in water more than 4,000 feet deep and that the sea gradually shallowed to about 900 feet by late Pliocene time (Natland, 1952, p. 50).
	Miocene	Upper	Capistrano siltstone	Tc		Basal breccia and sandstone.	Southeastern end of the basin.	Unconformably overlies the Monterey shale (middle Miocene).
		Middle and upper	Puente formation	Tpsc Tpy Tpsc Tplv Tpun	11,000	Divided by Schoellhamer et al. (1954) into four members: Sycamore Canyon member—interbedded conglomerate and micaceous siltstone and sandstone; Yorba member—thin-bedded gray siltstone, diatomaceous siltstone, and local sandstone and conglomerate; Soquel member—massive to moderately well-bedded, coarse to gritty, feldspathic sandstone and conglomerate; La Vida member—gray to black laminated cherty siltstone with interbedded feldspathic sandstone.	Crops out in the hills surrounding the basin; present beneath most of the alluvium-mantled central plain.	Sycamore Canyon and Yorba members, Soquel member, and La Vida member correspond to Upper, Middle and Lower members, respectively, of the Puente formation as defined by Eldridge and Arnold (1907, pp. 103, 143, 145). Rocks of late Miocene age and similar, in part, to both the Puente and Monterey formations are assigned to the Modelo formation in the Santa Monica Mountains west of Cahuenga Pass (Hoots, 1931).
			Monterey shale	Tm	600-2,000+	Organic to cherty shales, white weathering.	San Joaquin and Palos Verdes Hills bordering the ocean; probably present throughout the whole deep central portion of the basin.	Contemporaneous with lower part of the Puente formation, but deposited farther offshore and not clastic.

Table 1. Principal geologic formations in the Los Angeles basin, California.—Continued.*

System	Series	Stage	Unit (name)	Map symbol	Thickness (ft.)	General character and distinctive features	Known distribution	Remarks
TERTIARY—Continued	Miocene—Continued	Middle	San Onofre breccia	Tso	2,500+	Composed almost exclusively of fragments of glaucophane schist and related rocks of the western bedrock complex. Nonmarine with earthy matrix; marine, with sandy matrix.	San Joaquin Hills.	Interbedded with, and also unconformably overlain by, Monterey shale. Unconformably overlies the Topanga formation locally. Locally contains some marine mollusca.
			Topanga formation	Tt	7,500	Coarse tan and gray massive sandstone and conglomerate and dark gray shale; includes much intrusive and extrusive volcanic rock.	Northwest and southeast margins of the basin.	Buzzard Peak conglomerate of the northeastern San Jose Hills is correlated with the Topanga formation (Woodford et al., 1944).
			Volcanic and shallow intrusive rocks	Tvol	3,000	Mostly calcic andesite flows, tuffs, and breccias; large diabase and andesite sills and dikes.	Found in almost all parts of the basin. Most extensively exposed in Santa Monica Mountains and on north side of San Jose Hills.	Interbedded with upper part of the Topanga formation in the Santa Monica Mountains, also intrusive into Monterey shale (See Shelton, 1954, and Durrell, 1954).
	Oligocene & lower Miocene		Vaqueros formation	Tvs	3,200	Gray to buff sandstone, conglomerate, and, locally, greenish-gray sandstone.	Santa Ana Mountains, San Joaquin Hills, and probably Santa Monica Mountains.	Generally undifferentiated from conformably underlying Sespe formation. Marine fossils commonly present. Confined to lower Miocene.
			Sespe formation			Nonmarine interbedded earthy sandstone, conglomerate, and siltstone. Most commonly red, green, buff, and white.	Santa Ana Mountains, San Joaquin Hills, and Santa Monica Mountains.	Underlies marine Vaqueros formation and interfingers with it. Unfossiliferous in this region; probably ranges in age from late Eocene to earliest Miocene.
	Eocene		Santiago formation	Tsa	2,700±	Thin conglomerate at base. Fine- to medium-grained, buff to greenish gray sandstones grading upward into coarser feldspathic, white, massive sandstones containing local conglomerate lenses.	Santa Ana Mountains.	Correlated with the Tejon formation of central California by English (1926, p. 21), later renamed Santiago formation by Woodring and Popenoe (1945).
	Paleocene		Silverado formation	Tsi	1,400±	Sub-angular nonmarine conglomerate at base overlain by alternating series of white to buff feldspathic sands, commonly containing sufficient biotite flakes to resemble a biotite schist. Maroon pisolitic clay beds, a white clay bed, and low-grade lignite beds are interbedded in sands.	Silverado formation in Santa Ana Mountains, and probably beneath a considerable portion of the eastern part of the Los Angeles basin. Martinez formation common in parts of the Santa Monica Mountains.	Called Martinez formation in Santa Ana Mountains by Dickerson (1914, p. 263), renamed Silverado formation by Woodring and Popenoe (1945). In Santa Monica Mountains called Martinez formation by Hoots (1931, p. 91) and others. Important source of clay in Santa Ana Mountains.
CRETACEOUS	Upper		Williams formation	Kwp Kws	5,500	Pleasants silty sandstone member; Schulz Ranch sandstone and conglomerate member.	Santa Ana Mountains. Also in Santa Monica Mountains, not differentiated into members or formations.	"Chico" formation of Hoots (1931, p. 90); includes all Upper Cretaceous sedimentary rocks in Santa Monica Mountains; marine.
			Ladd formation	Klh Klb		Holz siltstone, sandstone, and conglomerate member; Baker Canyon conglomerate member.		
			Trabuco formation	Kt		Nonmarine red and white conglomerates and sandstones.		Conformable beneath Ladd formation in Santa Ana Mountains. Unconformable beneath "Chico" formation in Santa Monica Mountains (Durrell, 1954).
JURASSIC (?)			Western bedrock complex (Catalina schist)	pKc		Fine-grained, gray-green chlorite-bearing schists and local metamorphosed intrusive rocks. Glaucophane, lawsonite, actinolite and epidote are widespread but rarely abundant constituents.	Palos Verdes Hills; underlies Miocene rocks of Los Angeles basin southwest of the Newport-Inglewood fault zone.	One of world's largest masses of rocks belonging to the glaucophane schist facies. Catalina schist may be Mesozoic (Franciscan, cf.) or pre-Cambrian (texture cf. Pelona schist).
			Granitic intrusives	pKbc		Quartz dioritic rocks.	Santa Monica Mountains.	Provisionally dated as Jurassic by comparison with intrusions in the Sierra Nevada (Durrell, 1954) or Cretaceous (Larsen, 1948).

Table 1. Principal geologic formations in the Los Angeles basin, California.—Continued.*

System	Series	Stage	Unit (name)		Map symbol	Thickness (ft.)	General character and distinctive features	Known distribution	Remarks
OLDER ROCKS			Eastern bedrock complex	Santiago Peak volcanics	Jsp		Slightly metamorphosed flows, breccias, and tuffs, mostly of andesitic or quartz latitic composition.	Santa Ana Mountains.	
				Bedford Canyon formation (Triassic)	TRbc		Slightly metamorphosed slate, argillite, feldspathic sandstone, and subordinate limestone.	In the central part of the Santa Ana Mountains.	Lithologically similar, but unfossiliferous, black shale and graywacke occur in eastern part of the Santa Monica Mountains. Named Santa Monica slate by Hoots (1931); Santa Monica formation of Durrell (personal communication, 1954).
				Other rocks	pKbc		Limestone, schist, and plutonic rocks, mostly gabbro, quartz diorite, and granodiorite.	Bulk of ranges surrounding the Los Angeles basin to the north and northeast (Transverse Ranges). Underlie the eastern shelf of the basin.	Various rocks ranging in age from pre-Cambrian (?) to Jurassic.

* After Woodford et al. (1954), Hoots (1933), and others.

ments have been intruded by quartz-bearing plutonites of late Mesozoic age. Plutonic rocks are the commonest representatives of the basement terrane that has been penetrated by deep wells near the northern and eastern edges of the basin.

The principal features of the geologic formations of the Los Angeles basin are summarized in table 1, and the stratigraphic relationships are shown in figure 2. In general, the finer-grained sedimentary rocks of mid-Tertiary to Quaternary age were deposited in the central (and seaward) parts of the basin. The coarser material is confined largely to the margins, which correspond to the bordering hills of today.

Figure 3 shows the thickness of geologic strata of Upper Cretaceous through Pleistocene age in the Los Angeles basin. The columns represent sections measured from outcrops in the mountains and hills surrounding the present-day lowland area, as well as well-core data obtained in oil fields within the lowland area.

Structural Features. As the Tertiary and Quaternary sedimentary rocks accumulated in the Los Angeles basin and eventually filled it, they were continuously deformed by uplifts, downwarps, faulting, and folding. This deformation was most pronounced during late Pliocene and Quaternary time, and its effects can be seen at many places along the Whittier and Newport-Inglewood fault zones (figs. 4, 5). The structure of numerous folds is indicated by topographic rises in the lowland area of the basin.

The Whittier fault zone, which extends from Whittier east-southeastward to the Corona area, shows a vertical displacement of 10,000 feet or more, as well as possible right-lateral strike slip of 15,000 feet. The south side appears to have moved relatively westward and downward in the western Puente Hills and relatively westward and upward in the Santa Ana River area (Woodford et al., 1954).

The Newport-Inglewood fault zone extends northwestward from Newport Beach to Inglewood, a distance of 40 miles, and crosses the southwest part of the Los Angeles basin. At the surface it is distinguished principally by a series of en echelon hills that mark the positions and shapes of folds in which oil has accumulated. The folds appear to have developed in response to a strike-slip break that exists at depths of 10,000 feet or more in the underlying Catalina schist. Drill records indicate that the southwest side generally is 2,000 feet or more higher than the northeast side.

At Signal Hill the summit of a horst of subsurface schist is about 10,000 feet below sea level, or 4,000 feet higher than the schist surface immediately to the southwest.

The basin is divided structurally into fairly well-bounded blocks, mostly by major faults or fault zones (Woodford et al., 1954). The West Side block, southwest of the Newport-Inglewood fault zone, is separated from the Palos Verdes Hills block, still farther southwest, by the Palos Verdes fault zone. The Central Deep block underlies the lowland area northeast of the Newport-Inglewood fault zone, and is flanked by the Eastern shelf. The Eastern shelf is split by the Whittier fault zone into a northern or Puente Hills block and a southern or Anaheim-Santa Ana block.

The basement rocks southwest of the Newport-Inglewood fault zone (the Western bedrock complex) are low-grade metamorphic rocks characterized by abundant chlorite, quartz, muscovite, and albite, and particularly by the presence of glaucophane and lawsonite. They are similar to the Catalina schist (Jurassic ?) on Santa Catalina Island (Schoellhamer and Woodford, 1951).

The surface of this Western bedrock complex is exposed at an elevation of 1,000 feet above sea level in the Palos Verdes Hills, but it lies mostly at depths of 4,000 to 14,000 feet below sea level north of these hills. In the sedimentary cover, anticlines are draped over bulges or ridges in the crystalline floor. Each anticline is an oil field.

The Eastern shelf contains bedrock of pre-Cenozoic crystalline rocks (the Eastern bedrock complex) at depths that range from approximately sea level to at least 12,000 feet below sea level. These rocks include great plutonic masses that intrude metasedimentary and metavolcanic rocks ranging in age from Paleozoic to Jurassic (?). The intrusive rocks are mostly gabbro, quartz diorite, and granodiorite. The eastern bedrock complex probably underlies the main part of the Central Deep at depths greater than 20,000 feet.

Geomorphic Features. The geomorphic features of greatest interest in the Los Angeles basin are those that illustrate the recency of deformation. The elevation of the coastal areas in late Pleistocene time is shown by the development of numerous wave-cut marine terraces, particularly in the Palos Verdes Hills, the San Joaquin Hills, and the Santa Monica area. The highest terrace yet recognized is in the Palos Verdes Hills, and lies at an elevation of 1,300 feet above sea level. Most of the terraces are horizontal or nearly so, but the lower terrace on the northeast flank of the Palos Verdes Hills has been deformed by movement along the Palos Verdes fault. Mesas west of the San Joaquin Hills dip inland beneath the alluvial cover, and they may have been tilted during movement along the Newport-Inglewood fault zone.

Relatively recent uplift is suggested by remnants of fluviatile terraces along the larger streams of the Santa Ana Mountains. Several of these terraces can be observed in Santa Ana Canyon.

The streams of the Los Angeles basin, most of which head in the San Gabriel Mountains, cut through ridges and hills that have been uplifted while the streams maintained their courses. Thus the Los Angeles, San Gabriel, and Santa Ana Rivers seem to be antecedent to the uplift of the Santa Ana-Santa Monica Mountains and the low hills of the Newport-Inglewood fault zone. The wide channel of the San Gabriel River across the Seal Beach oil field is an example of continued erosion across a gradually rising surface. In some places, as at Coyote Pass in the Repetto Hills, wind gaps were formed when uplift became more rapid than the rate of down-cutting by streams.

AGE	ROCK UNITS		
	SANTA ANA MOUNTAINS and SAN JOAQUIN HILLS	NORTH AND CENTRAL LOS ANGELES BASIN	SANTA MONICA MOUNTAINS
Upper and Middle (?) Pliocene	Rocks commonly called "Pico"		
Lower Pliocene (?)		Repetto	
Upper Miocene	Capistrano Monterey	Puente	Modelo
Middle Miocene	San Onofre Topanga	Topanga	Topanga
Upper Eocene (?) to Lower Miocene	Vaqueros-Sespe		Vaqueros & Sespe
Middle Eocene	Santiago		
Paleocene	Silverado		Martinez (?)

FIGURE 2. Inferred stratigraphic relationships of Tertiary formations in the Los Angeles basin, California.

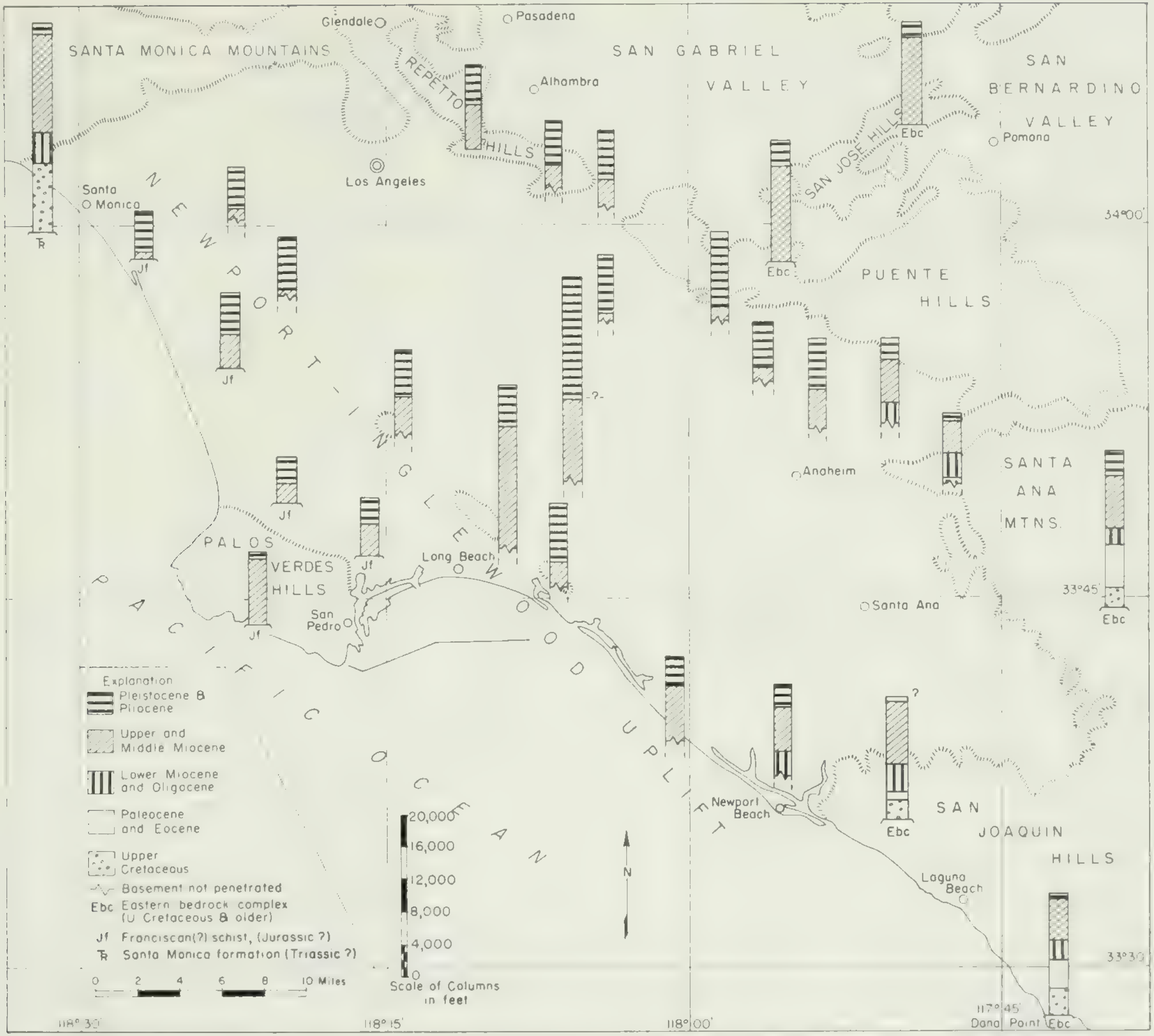
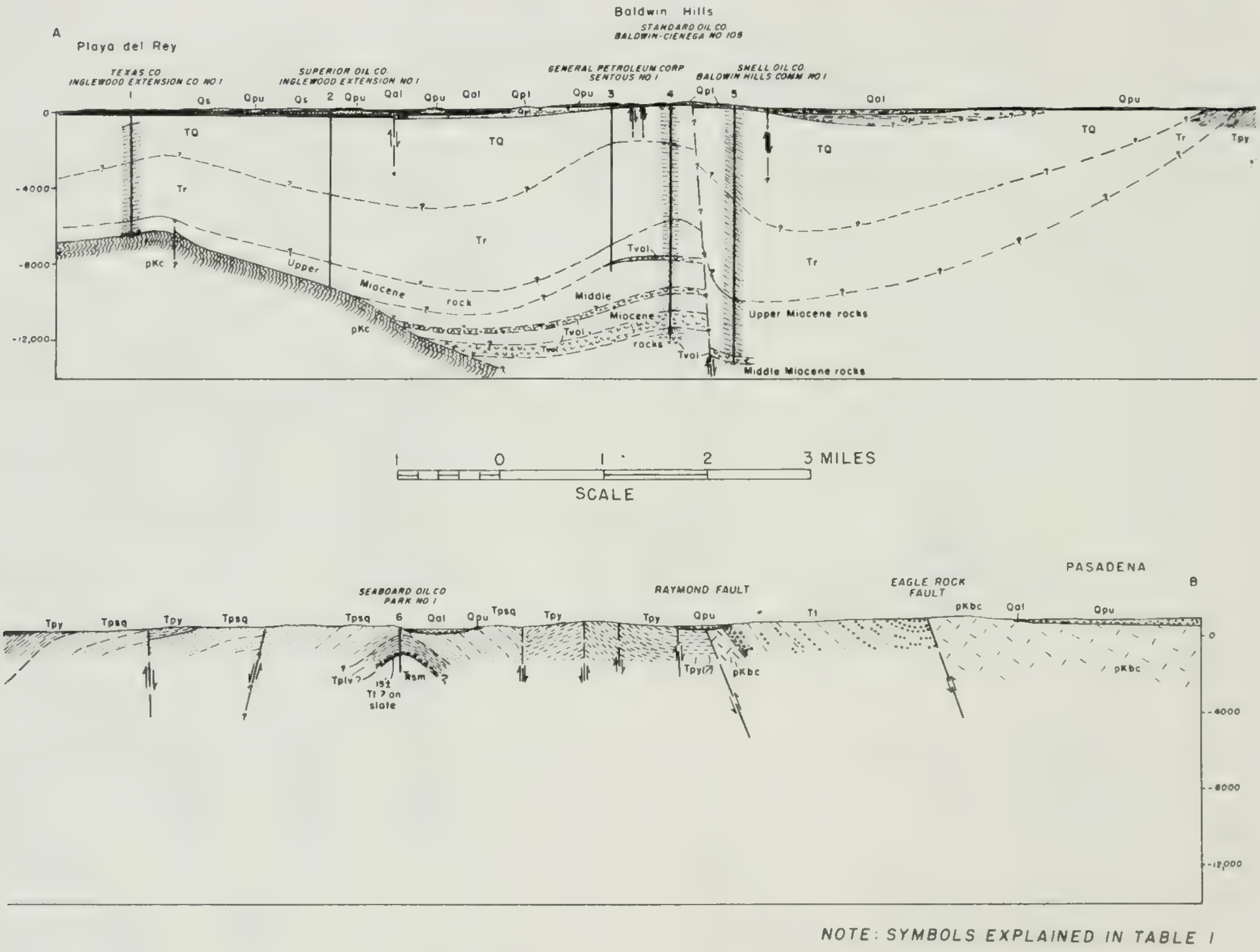


FIGURE 3. Generalized columnar sections in the Los Angeles basin, California.


A
Playa del Rey
Baldwin Hills
STANDARD OIL CO. BALDWIN-CIENEGA NO 105
TEXAS CO INGLEWOOD EXTENSION CO NO 1
SUPERIOR OIL CO. INGLEWOOD EXTENSION NO 1
GENERAL PETROLEUM CORP SENTOUS NO 1
SHELL OIL CO. BALDWIN HILLS COMM NO 1
1
2
3
4
5
Qs
Qpu
Qal
Qpl
TQ
Tr
Tvol
pKc
Upper Miocene rock
Middle Miocene rocks
Upper Miocene rocks
Tpy
0
-4000
-8000
-12,000
1 0 1 2 3 MILES
SCALE
SEABOARD OIL CO PARK NO 1
6
RAYMOND FAULT
EAGLE ROCK FAULT
PASADENA
B
Tpsq
Tplv ?
15½
Tt ? on slate
R̶sm
Tpy(?)
pKbc
Tt
NOTE: SYMBOLS EXPLAINED IN TABLE I

STRUCTURE SECTION A-B, PLAYA DEL REY TO PASADENA

FIGURE 4. Structure section A-B across the northwestern part of the Los Angeles basin, California, from Playa del Rey to the Repetto Hills.

Table 2. Oil fields in the Los Angeles basin, California.

Name	Discovery date*	Age of producing formations*	Structure††	Production (thousands of barrels)*	
				1952	Total to Jan. 1, 1953
Alondra	Aug. 1946	Miocene	Dome over basement high	92	1,191
Belmont off-shore	Nov. 1948	Miocene	Asymmetrical dome	11	50
Beverly Hills	July 1900	Pliocene	Anticline	29	4,156
Brea-Olinda	1899	Pliocene, Miocene	Narrow, faulted anticlines	6,928	220,049
Coyote East	1917	Pliocene, Miocene	En Echelon domes	2,740	65,121
Coyote West	1909	Pliocene, Miocene	Anticline	3,335	175,823
Dominguez	Sept. 1923	Pliocene, Miocene	Faulted anticline	3,887	196,055
Dominguez, East	Feb. 1946	Pliocene, Miocene	Faulted anticline	6	53
East Los Angeles	Feb. 1946	Pliocene, Miocene	Dome	341	2,813
El Segundo	Aug. 1935	Miocene	Compacted dome over basement high	90	12,433
Huntington Beach	Aug. 1920	Pliocene, Miocene	Faulted monocline, dome	21,789	502,699
Hyperion	1944	Catalina schist		25	208
Inglewood	Sept. 1924	Pliocene, Miocene	Faulted anticline	4,984	184,774
Kraemer	Sept. 1918	Miocene	West-plunging anticline	48	1,890
Lawndale	Dec. 1928	Miocene	Dome over basement high	160	2,189
Long Beach	June 1921	Pliocene, Miocene	Faulted anticline	7,963	766,300
Los Angeles	1892	Miocene	Flexure on large anticline	56	20,409
Montebello	Feb. 1917	Pliocene, Miocene	Anticline	1,916	159,442
Newport-Mesa	July 1947	Miocene	Fault (?)	1	12
Newport-West	1943	Miocene	Northwest-plunging nose	1,453	14,517
Playa del Rey	Dec. 1929	Pliocene, Miocene	Anticline over basement ridge	585	56,240
Potrero	Apr. 1928	Pliocene, Miocene	Faulted dome	333	8,314
Puente Hills	1880	Miocene	Faulted homocline	39	3,405
Richfield	Mar. 1919	Miocene	Faulted anticline	2,412	119,168
Rosecrans	May 1924	Pliocene, Miocene	Anticline	1,684	70,120
Salt Lake	1902	Miocene	Faulted anticline	77	43,236
Sansinena	May 1945	Pliocene, Miocene	Faulted, plunging anticline	1,929	3,714
Santa Fe Springs	July 1921	Pliocene, Miocene	Anticline	5,164	543,796
Seal Beach	1926	Pliocene, Miocene	Faulted anticline	4,083	130,711
Torrance	June 1922	Pliocene, Miocene	Plunging anticline	2,510	135,795
Turnbull	Oct. 1941	Miocene	Faulted anticline	22	613
Whittier	1898	Pliocene, Miocene	Faulted homocline	259	22,014
Wilmington	Apr. 1934	Pliocene, Miocene	Faulted anticline	48,121	605,814
Yorba Linda	Dec. 1937	Pliocene	Anticline	291	3,347

* From Annual Review, 1952, Conservation Committee of California Oil Producers.
†† Compiled from various sources.

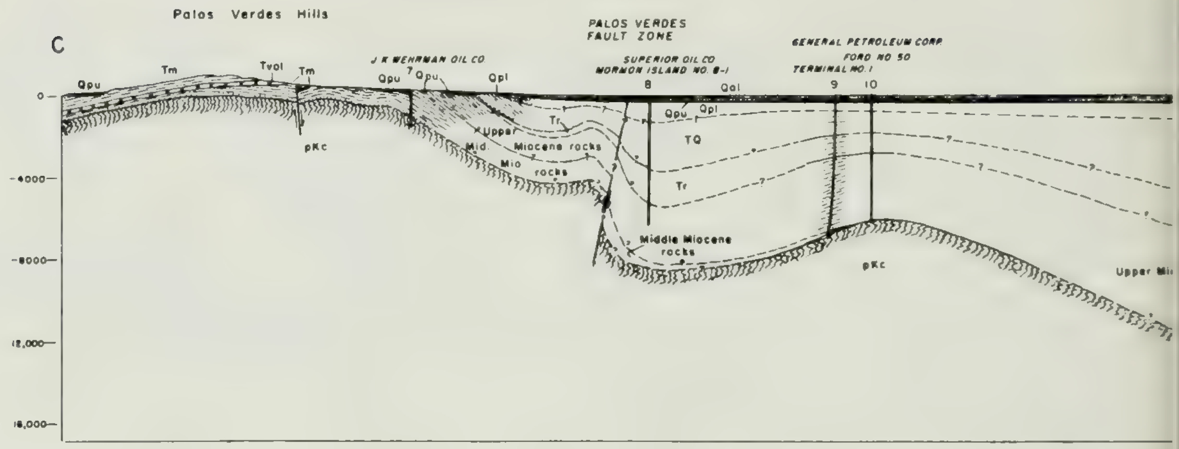
The streams have produced surfaces that are partly erosional and partly depositional. Depositional features are the alluvial fans and washes in areas where streams debouch onto the lowlands of the Los Angeles basin. The most notable erosional features are relatively flat surfaces within the mountainous or hilly areas.

Deformation of the Los Angeles basin appears to be continuing at the present time. Accurate level surveys indicate, in general, that the center of the basin is subsiding and the margins are rising. Santa Ana subsided 1.568 feet between 1920 and 1946, and central Long Beach 0.768 foot between 1926 and 1946 (Woodford et al., 1954). The maximum subsidence of about 18 feet in the last 20 years has occurred in the Wilmington area, near the center of the Wilmington oil field.

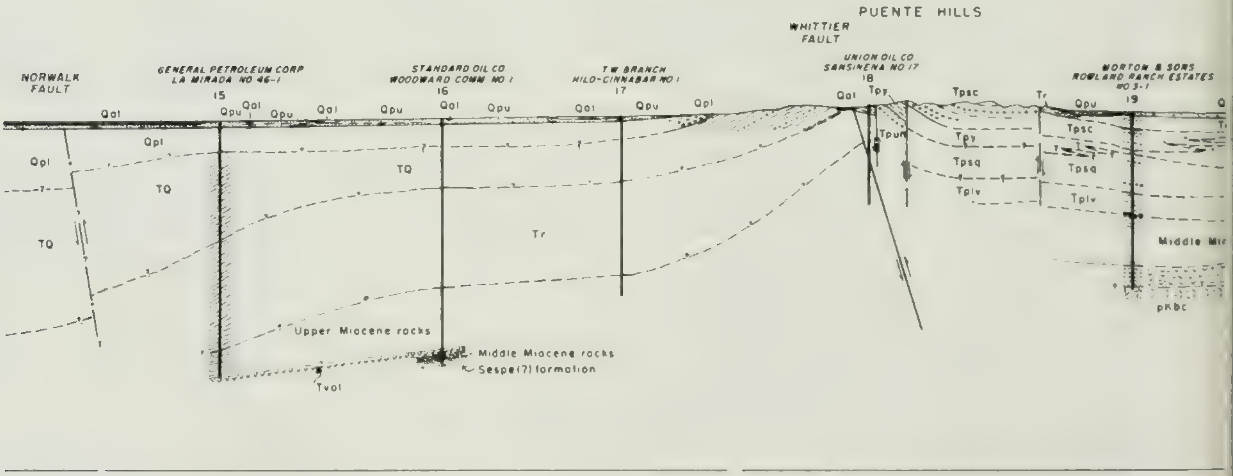
Petroleum. Figure 6 shows the location of the principal oil fields in the Los Angeles basin, which has yielded more than 4 billion barrels of oil since 1880. More than 40 percent of California oil production has been obtained from an area of approximately 40,000 acres, representing a recovery of more than 100,000 barrels per acre for the average of the proved fields. Twelve of the 40 fields in the basin have yielded more than 100 million barrels apiece.

The largest amount of oil is obtained from the Repetto (lower Pliocene) formation, and much of the remainder from the uppermost part of the upper Miocene section. A comparatively small amount is obtained from upper Pliocene and middle Miocene rocks, and from fractured schist of Jurassic (?) age.

About 1,600,000,000 barrels of oil have been extracted from faulted anticlines along the Newport-Inglewood uplift. Some 900,000,000 barrels have been obtained from a series of folds extending from Santa Fe springs to the Richfield area near the central part of the basin. The remaining fields yield oil from anticlines, fault traps, and

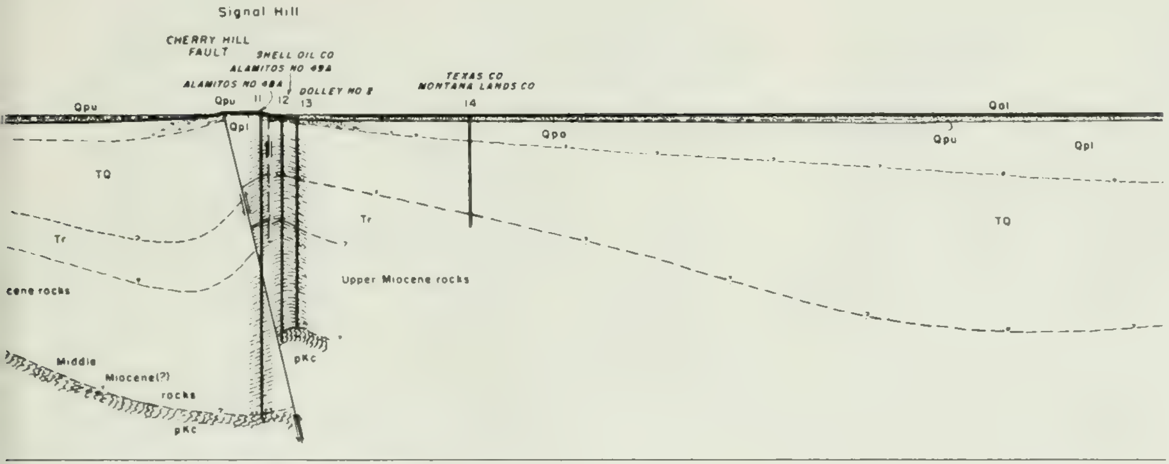


SOUTHWESTERN PART OF SECTION C-D



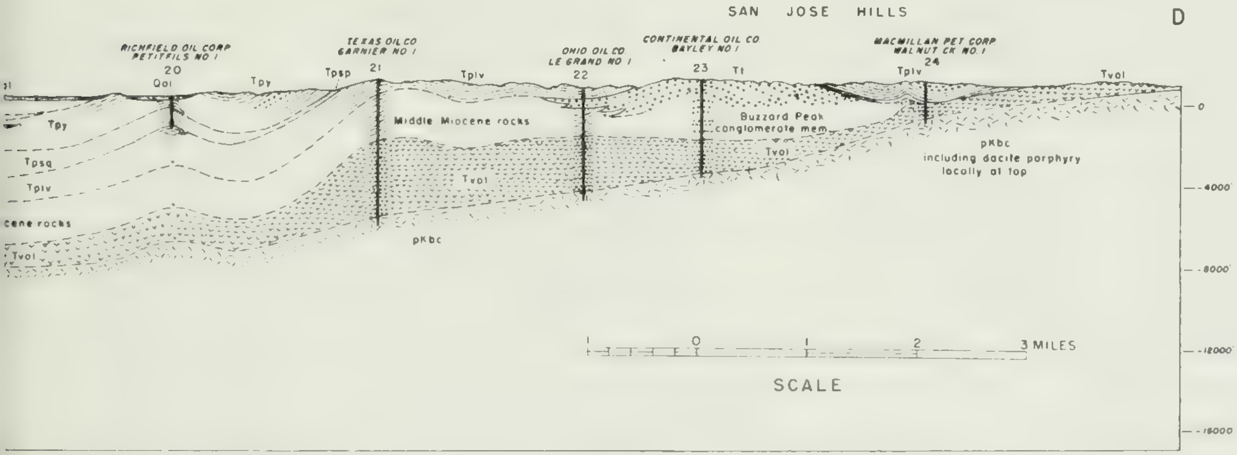
NORTHEASTERN PART OF SECTION C-D

FIGURE 5. Structure section C-D across the central part of the Los Angeles



PALOS VERDES HILLS TO MOUNTAIN MEADOWS

NOTE: SYMBOLS EXPLAINED IN TABLE I


SAN JOSE HILLS
D
RICHFIELD OIL CORP PETITFILS NO 1
TEXAS OIL CO GARNIER NO 1
OHIO OIL CO LE GRAND NO 1
CONTINENTAL OIL CO BAYLEY NO 1
MACMILLAN PET CORP WALNUT CK NO. 1
21
20
21
22
23
24
Qol
Tpy
Tpsp
Tplv
Tt
Tplv
Tvol
Tpy
Tpsq
Tplv
cene rocks
Tvol
Middle Miocene rocks
Buzzard Peak conglomerate mem
Tvol
Tvol
pKbc
pKbc including dacite porphyry locally at top
0
4000'
8000'
12000'
16000'
1 0 1 2 3 MILES
SCALE

PALOS VERDES HILLS TO MOUNTAIN MEADOWS

basin, California, from the Palos Verdes Hills to the San Jose Hills.

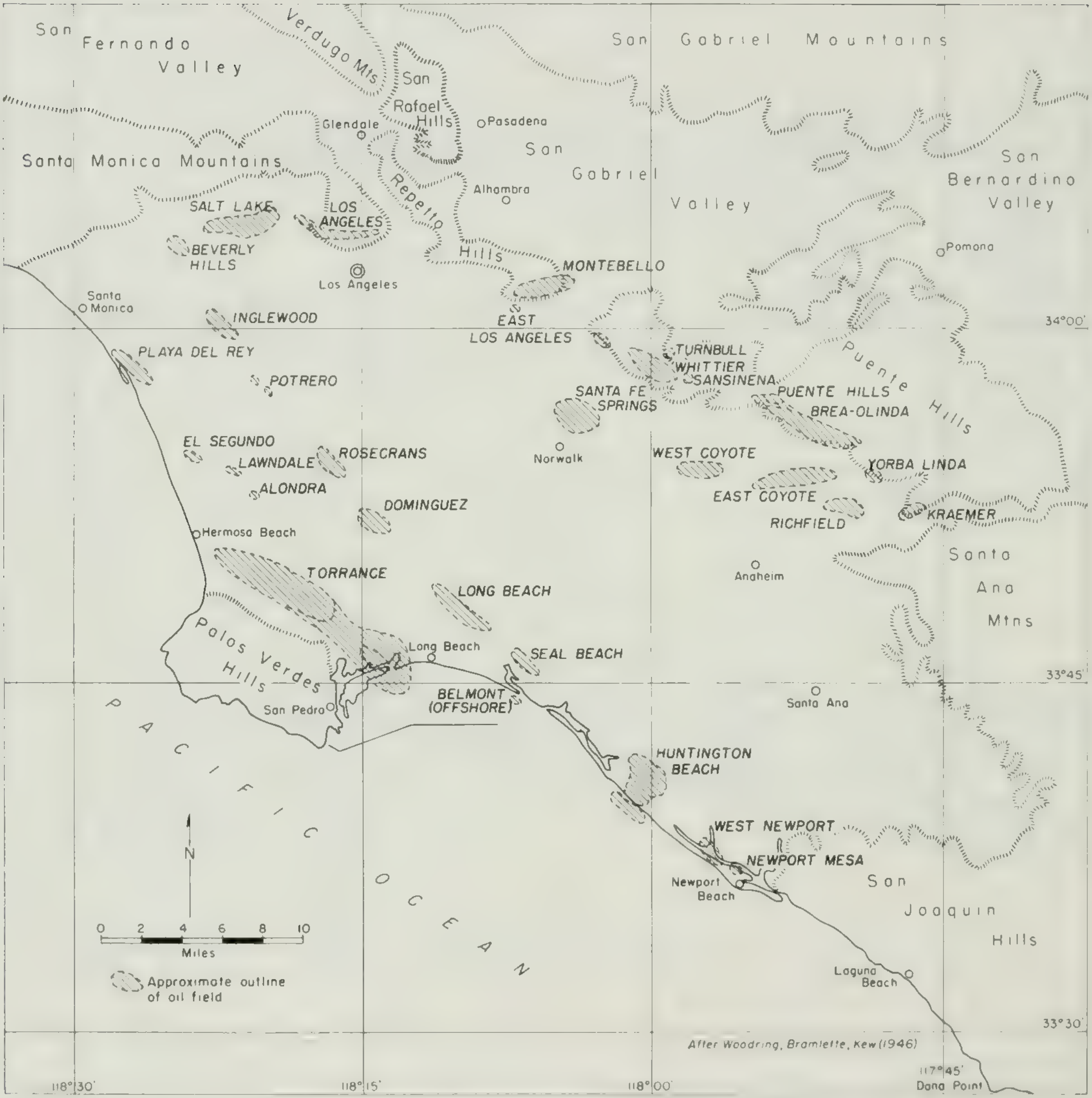


FIGURE 6. Index map of oil fields of the Los Angeles basin, California.

stratigraphic traps, commonly near the margins of the basin. The Torrance and Wilmington fields have yielded about 700,000,000 barrels of oil from a broad arch extending along the northeast margin of the Palos Verdes Hills.

Table 2 provides data on the principal oil fields in the basin.

ROADLOG

Los Angeles to Montebello

The first segment of the tour of the Los Angeles basin begins at First Street and Broadway, proceeds northeast on Broadway to the Hollywood Freeway, and thence eastward to and along the Ramona Freeway.

Downtown Los Angeles is near the northern margin of the Los Angeles basin. Outcrops in this area show a south-dipping section of Pliocene marine sedimentary rocks that rest conformably on upper Miocene marine shale and sandstone of the Puente formation. The rocks of this section, covered to the south by Recent alluvium, form the flanks of the west-trending Elysian Park anticline, a fold that extends through the eastern part of the Elysian Park Hills and into the Repetto Hills east of the Los Angeles River (Map 1).

The Los Angeles River is crossed east of the Los Angeles Union Station. Here the river emerges from the Los Angeles Narrows between the Santa Monica Mountains (Elysian Park Hills) and the Repetto Hills. Near the south end of the narrows the Los Angeles River is probably antecedent, as it apparently has maintained its course across the Elysian Park anticline during the development of this structural feature in late Pliocene and Pleistocene time. Below the narrows the river flows across the Los Angeles basin and into the sea at Long Beach (fig. 1). In very recent geologic time, the course of the river immediately south of the narrows has fluctuated between its present channel and a more westerly one that lies north of the Baldwin Hills. This alternate channel, now occupied by Ballona Creek, reaches the ocean south of Venice.

The Repetto Hills, southeast (right) of the Ramona Freeway, are a west-trending extension of the Puente Hills. They are underlain by a thick homoclinal section of south-dipping Pliocene and Miocene sandstone, siltstone, mudstone, and shale exposed in roadcuts along the freeway.

The San Gabriel Mountains, the most prominent of the Transverse Ranges, can be seen from the Ramona Freeway. They are underlain principally by plutonic rocks that range from pre-Cambrian through Jurassic (?) in age, and from norite through granite in composition. Several types of metasedimentary rocks of pre-Cretaceous age also are present. The bold-faced range has been uplifted along steeply dipping reverse faults during late Tertiary and Quaternary time. Most of the streams that cross the Santa Ana-Puente Hills-Santa Monica Mountains belt rise in the San Gabriel Mountains or in adjoining ranges to the east and west.

Coyote Pass, a wind gap through the Repetto Hills, is traversed by Coyote Pass road, which is accessible by turning right (south) onto Fremont Avenue from the Ramona Freeway [5.9]. A south-flowing stream must have once extended through this pass and thence across the lowland to the south, probably in late Pleistocene time. Later the stream channel and adjacent hills were elevated more rapidly than the stream could erode downward, and thus the wind gap was formed. The pass traversed by Atlantic Boulevard half a mile east of Coyote Pass has had a more complex history. Originally a water gap, it was a wind gap for a short time and is now a water gap again. Its present stream drains the north part of Coyote Pass.

The type section of the Repetto formation (lower Pliocene) is exposed along Atlantic Boulevard in the Repetto Hills. The formation consists of 2,000 to 2,500 feet of micaceous siltstone and a little interbedded sandstone, and rests conformably upon shale and siltstone of the Puente formation (upper Miocene). The top of the Repetto formation has been designated as the top of the highest of three beds of coarse feldspathic sandstone (Reed, 1933b, p. 31), but it is currently assigned to higher levels by oil-company geologists. The Repetto formation is distinguished from the conformably overlying Pico formation (upper Pliocene), which is lithologically similar, primarily on the basis of microfossils. The type Pico formation is in the eastern Ventura basin, 25 or 30 miles to the northwest. Its lower part contains characteristic Repetto microfaunas and is probably of the same age as the upper part of the type Repetto formation.

At Stop 1 [8.0] phenomena attributable to ancient mass movement of marine sediments are exposed in the cliff at the rear of the parking area for the Floral drive-in theater. Contorted lenses of conglomerate, containg *Pecten bellus* and other Pliocene megafossils that almost certainly are shallow-water forms, are surrounded by and intermixed with massive mudstone containing Pliocene Foraminifera characteristic of deep-water environment. Isolated pebbles and limestone concretions of irregular shape are scattered through the mudstone. Slickensides are present at the base of conglomerate lenses and around some of the isolated pebbles. These beds and pebbles probably were first deposited in nearshore areas, and later either slid or were transported by turbidity flows to the base of a steep underwater slope. The mudstone, of deeper-water origin, apparently was folded and mixed with the conglomerate during the downward movement. The turbidity flows probably travelled in a southerly direction, and may have been triggered by fault movements. Although these units of mixed rocks are not continuous for more than a few hundred feet, they apparently occur at about the same stratigraphic position in several localities, and have been used as a marker horizon in the otherwise monotonous section of Pliocene siltstone and mudstone.

Mudstone from Pliocene strata north of the drive-in theater is the raw material used at the brickyard south of the theater.

Proceed south on Mednick Avenue, thence left (east) on Third Street and Pomona Boulevard. Follow Potrero Grande Drive northeast through a thick section of flat-lying upper Pleistocene nonmarine sand and gravel in the Repetto Hills. Several roadcuts provide excellent exposures of these sediments.

Turn right (east) on Arroyo Drive [12.7]. At mile 13.3 a thick section of upper Pleistocene nonmarine strata is exposed in the west face of the quarry of the Owl Rock Products Company. These strata constitute a large reserve of aggregate.

Montebello Oil Field. The Montebello oil field, north of the town of Montebello, has yielded oil from four zones in Repetto (lower Pliocene) strata, as well as from upper Miocene strata. The zones are extremely lenticular, as are the sandstones and conglomerates that constitute most of the Repetto formation in this area. The oil has accumulated along the crest of a west-trending, east-plunging, elongate anticline.

Pleistocene sand and conglomerate, mostly of terrestrial origin, flank the hills and locally occur on their summits. These strata unconformably overlie the Pico (upper Pliocene) formation, here composed of marine silt and fine sand that are exposed along the axis and at the crest of the anticline. The upper Pliocene strata extend only to a depth of about 800 feet in the Montebello oil field. The Repetto (lower Pliocene) formation is 4,700 feet thick near the western end of the field and thickens to the northwest, but the total thickness under most of the field is not known (Reese, 1943, p. 340). A few wells have encountered Miocene strata at a depth of about 5,500 feet below sea level.

Proceed to Rosemead Boulevard, thence right (south).

The Rio Hondo channel of the San Gabriel River is crossed near its entrance into the Whittier Narrows, a gap between the Puente and Repetto Hills that is shared by two branches of the San Gabriel River. The Rio Hondo swings westward below the narrows and joins the Los Angeles River near Downey (fig. 1). The other, or main, channel of the San Gabriel River flows southward to the sea near Seal Beach. About 4 miles south of the Whittier Narrows the San Gabriel River, during Quaternary time, planed off much of a rising anticlinal fold in the Santa Fe Springs area. During the final stage of the uplift the river was deflected around the west margin of the fold, and the present slight topographic expression of the fold was thereby preserved.

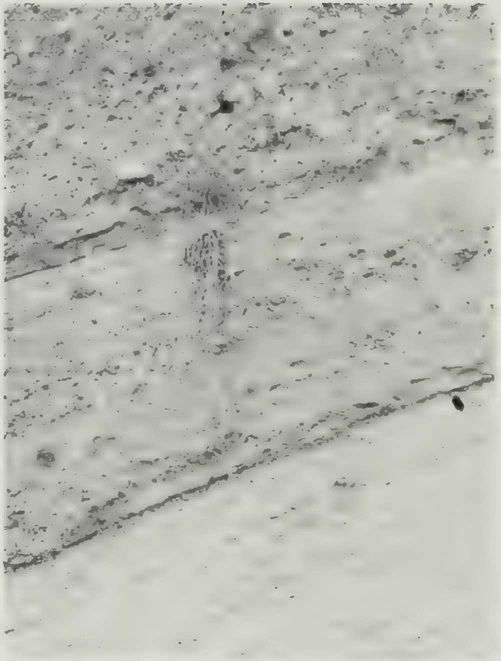


FIGURE 7. Conformable contact between fine-grained sandstone or siltstone and conglomerate of the Sycamore Canyon member of the Puente formation (upper Miocene). Clasts of siltstone are included in the overlying conglomerate.

The narrows contain Recent alluvium that occupies a trough cut in upper Pleistocene alluvium. The older alluvium probably is part of a fan that was dissected at its head below the narrows and then was partly covered by alluvium in the present river channels.

Natland has suggested (Kundert, 1952, p. 7) that coarse detritus in the Repetto formation of this area was transported through the Whittier Narrows, and that here the main channel of deposition during lower Pliocene time closely approximated the course of the present San Gabriel River. He believes that this Pliocene channel is marked by a belt of coarse sedimentary rocks extending from the Whittier Narrows to Long Beach.

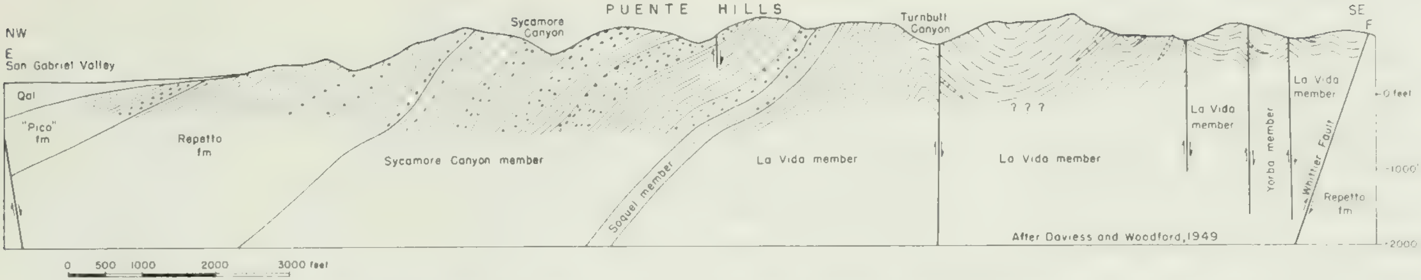


FIGURE 8. Structure section E-F through the Puente Hills north of Whittier, California, showing structure north of the Whittier fault.

An earth-fill dam, constructed in 1954 across the Whittier Narrows by the U. S. Army Engineers, is a large flood-control structure.

At Beverly Boulevard [16.5] turn left (east) and proceed to Stop 2 (Map 2), near the crest of the Puente Hills on Turnbull Canyon Road.

The Puente formation, subdivided into four members, the La Vida, Soquel, Yorba, and Sycamore Canyon, in ascending order, occurs throughout the Puente Hills. The La Vida and Sycamore Canyon members are exposed along Turnbull Canyon Road. Conglomerates of the Sycamore Canyon member, exposed at Stop 2, are composed mostly of well-rounded pebbles and cobbles of crystalline rocks that probably were transported many miles, but they also contain fragments of Tertiary marine strata that are too fragile to have been transported far by ordinary media. These clasts of marine strata probably were derived locally and emplaced by submarine flows of sand and silt. Graded bedding is featured in lenses of sandstone. The base of one of the large conglomerate units rests with remarkable conformity upon thin-bedded siltstone (fig. 7).

Continue uphill to Skyline Drive, turn around, return to Painter Avenue [24.8], and turn left (south) to Whittier Boulevard [26.4].

Whittier to Brea Oil Field

The route of travel from Whittier is southeasterly along the south flank of the Puente Hills. The red soil, common in this area and typical of that developed on the older alluvium (Pleistocene), is excellent for agricultural purposes, especially for the growing of citrus trees.

The Whittier fault zone extends through the Puente Hills southeastward from the Whittier Narrows to the Santa Ana River. It is a major structural feature of the Los Angeles basin, and is encountered at several points along the route of the trip. In this area the principal movement has occurred along the southernmost branch of the fault zone, which dips north at an angle of about 70 degrees. The north side has been thrust up about 7,000 feet relative to the south side (fig. 8). Stream offsets indicate that right-lateral displacement of 4,000 to 5,000 feet also has occurred along the fault zone 2 or 3 miles east of this area. The Tertiary strata north of the fault zone have been closely folded and broken into elongate fault blocks, whose principal axes generally are parallel to the main fault zone. South of the Whittier fault zone most of the Tertiary strata dip southward in a gently warped homoclinal sequence.

Whittier Oil Field. The Whittier oil field, on the southern slope of the Puente Hills east of Whittier, is the most westerly of the fields that have been developed along the Whittier fault zone. Several smaller fields border the main productive area.

The oil is contained in several zones within the Repetto (lower Pliocene) and Puente (upper Miocene) formations, which form a south-dipping homocline. The homocline occurs on the down-dropped block south of the Whittier fault zone.

The Coyote Hills rise south of Whittier Boulevard and east of Whittier. They show much greater relief than the Santa Fe Springs area, although their structural evolution has been similar. They mark the position of an anticline that was continuously planed off by erosion during much of its growth. During the later stages of growth, the rate of uplift exceeded the rate of erosion, and the hills thus rose as a nearly smooth-surfaced dome that only now is beginning to develop a drainage pattern (fig. 9).

In the vicinity of the Brea-Olinda oil field, stream offsets indicate a right-lateral displacement of at least 1½ miles along the Whittier fault zone (fig. 10). From the intersection of Central Avenue and

Brea Canyon Road [35.1] to Stop 3, the observer follows the course of a stream offset along the fault.

Strata of the Repetto formation (lower Pliocene) underlie the hill south of Stop 3. These beds dip steeply south near the fault zone, but gradually flatten to the south. They contain microfaunas that are generally believed to be indicative of deep-water environments.

Tightly folded beds of the Soquel and Yorba members of the Puente formation occur between branches of the fault zone at the Brea oil field. Although the field has been productive for 55 years, its subsurface structure is not entirely known. Many of the surface features in the part of the oil field west of Stop 3 are attributable to landslides, which have hindered geologic interpretations in this area.

The strata north of the Whittier fault zone form a thick section of the Puente formation, and include a minor amount of intrusive volcanic rocks near the fault.

Brea Oil Field to Pomona

Three poorly exposed branches of the Whittier fault zone are traversed just north of Stop 3. Roadcuts expose upper Pleistocene nonmarine strata east of Stop 3.

North through the Puente Hills are roadcut exposures of the Puente (upper Miocene) formation, which elsewhere is mostly concealed beneath surficial material in this area of rolling terrain (fig. 11). The upper part of the La Vida siltstone, the lowest member of the Puente formation, is exposed for the first mile, to the Diamond Bar Ranch house, and thence the Soquel sandstone appears in the prominent cuesta northwest of the road. The overlying Yorba siltstone is exposed along the north side of the strike valley beyond mile 41, and the still higher Sycamore Canyon member (conglomerate, siltstone, and sandstone) is out of sight to the north. A minor anticline in beds stratigraphically near the top of the Soquel member is exposed in the roadcut at mile 40.7.

Beyond mile 43 (Map 3) the road traverses a thinner and conglomeratic section of the Soquel member near its northeastern limit. These strata are sharply upturned, and their south dips are in contrast to the nearly flat-lying sandstone beds that crop out in the hills to the southeast. The beds in the two areas probably were deposited contemporaneously. A few large boulders, some as much as 8 feet in diameter, lie on the sandstone exposures and probably have been weathered out of immediately overlying beds. The beds of conglomerate and sandstone probably are slightly higher in the Soquel section than most of the beds exposed elsewhere in the area.

The Soquel conglomerate rests directly on andesite flows and breccias of probable middle Miocene age near the northern crest of the hills (Stop 4). The volcanic rocks underlie most of the northern slope of this part of the Puente Hills. These rocks exhibit flow banding and breccia and are well exposed in roadcuts at Stop 4 (fig. 12).

The volcanic rocks here are about 700 feet thick. They thin to the southeast and thicken to the northwest, and similar volcanic rocks are as much as 3,500 feet thick beneath Covina (Shelton, 1954). They are part of the Glendora volcanic series, and perhaps are contemporaneous with the volcanic rocks in the Topanga formation (middle Miocene) of the Santa Monica Mountains (see Durrell, 1954). Other volcanic rocks of middle Miocene age are exposed in the Santa Ana Mountains, the San Joaquin Hills, and in the Palos Verdes Hills.

The Glendora volcanics lie unconformably on Mesozoic plutonic rocks that are exposed in grass-covered spurs along the north flank of the Puente Hills east of Stop 4 (Map 3) and southwest of Pomona. These intrusive rocks are similar to rocks of the Perris block (Larsen, 1948), 25 miles to the east-southeast.

Pomona Area to Prado Dam

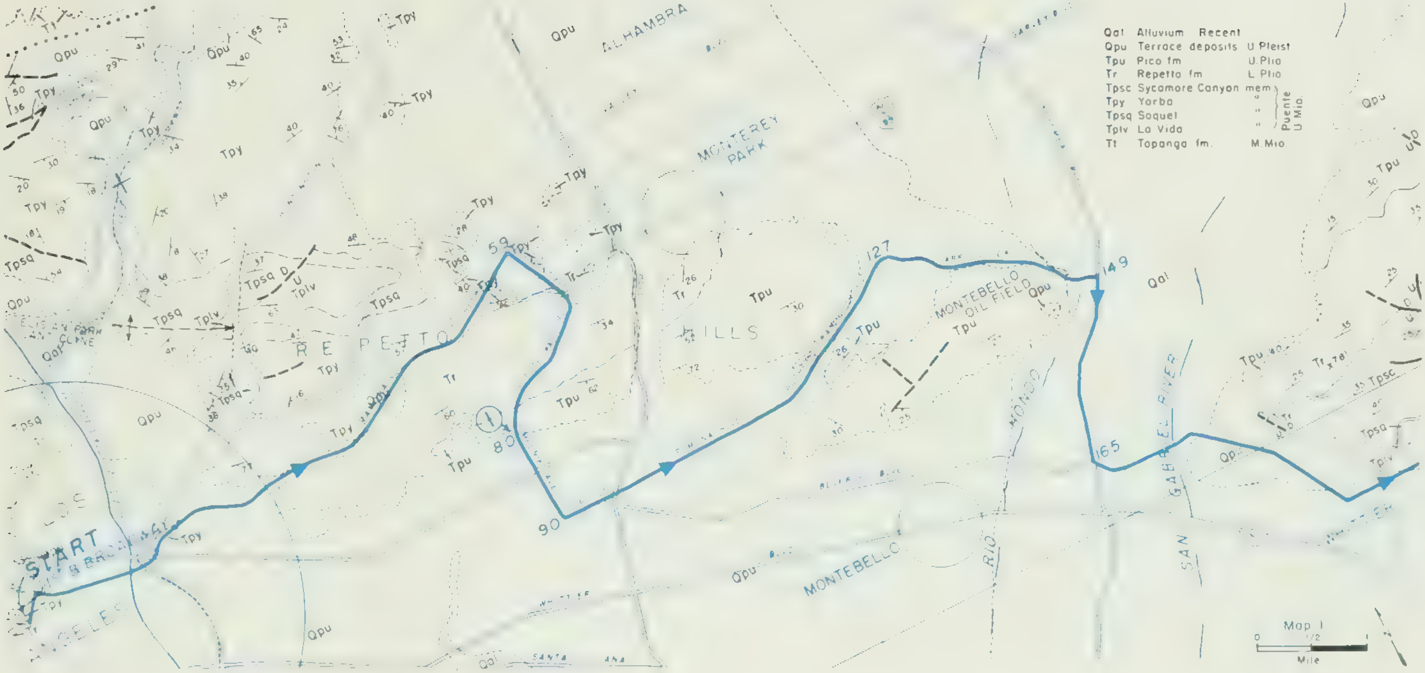
Continue northeast on Brea Canyon Road to Fifth Avenue, and thence south along Garey Avenue [48.1]. Turn left (southeast) and follow State Highway 71 to Merrill Avenue [53.7], turn left (east) onto Pomona-Rincon Road [54.8], and follow this road southeast to Euclid Avenue [58.9].

The San Jose Hills and the Puente Hills form the western and southern margins of the San Bernardino Valley. Most of the valley soil is developed on alluvium derived from the San Gabriel Mountains to the north, and is utilized for vineyards and citrus groves. The southwestern part of the valley is underlain by at least 1,300 feet of continental Quaternary deposits and several thousand feet of marine sedimentary rocks of probable Pliocene and upper Miocene age (Woodford et al., 1944).

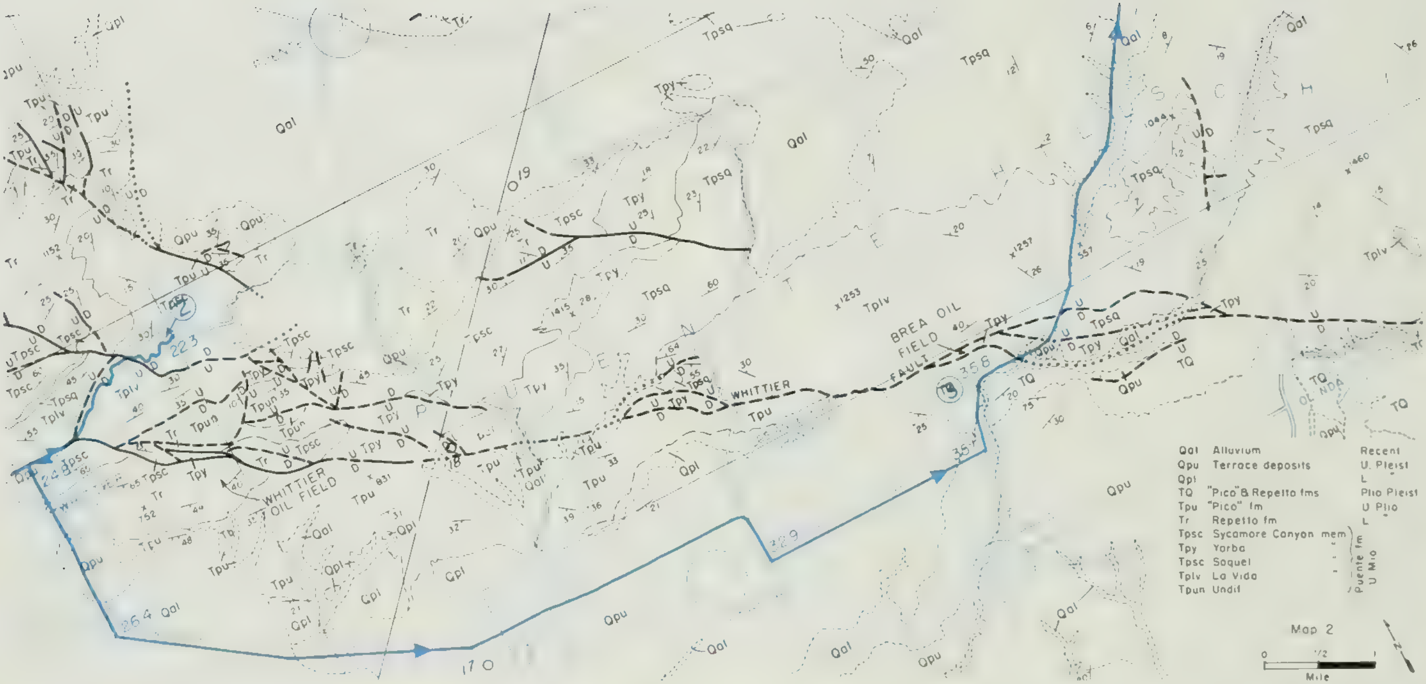
The straight northwest boundary between the San Bernardino Valley and the Puente Hills southeast of mile 53.7 is parallel to the Chino fault, although the actual trace of this high-angle reverse fault is on the flank of the Puente Hills.

The fault trends southeast and dips steeply southwest. It places Pliocene conglomerate on the northeast against upper Miocene sandstone, siltstone, and conglomerate on the southwest. The road crosses the fault at mile 60.5. The fault is concealed by alluvium just east of Prado Dam (Map 4), and disappears beneath terrace deposits west of Corona.

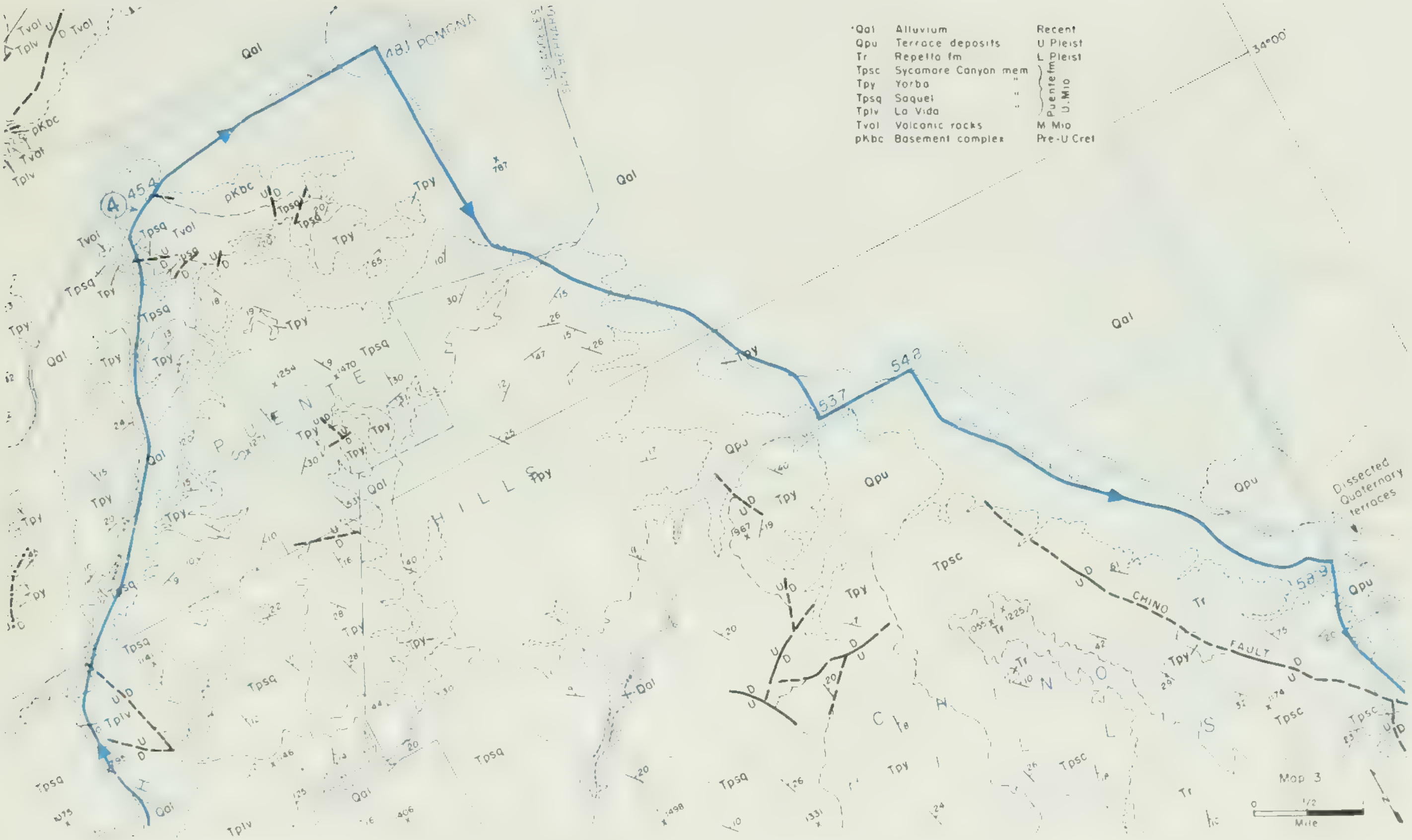
The rolling terrain north of the intersection of Pomona-Rincon Road and State Highway 71 [58.9] marks a series of dissected terraces of Quaternary gravel. Both the gravel and underlying Pliocene



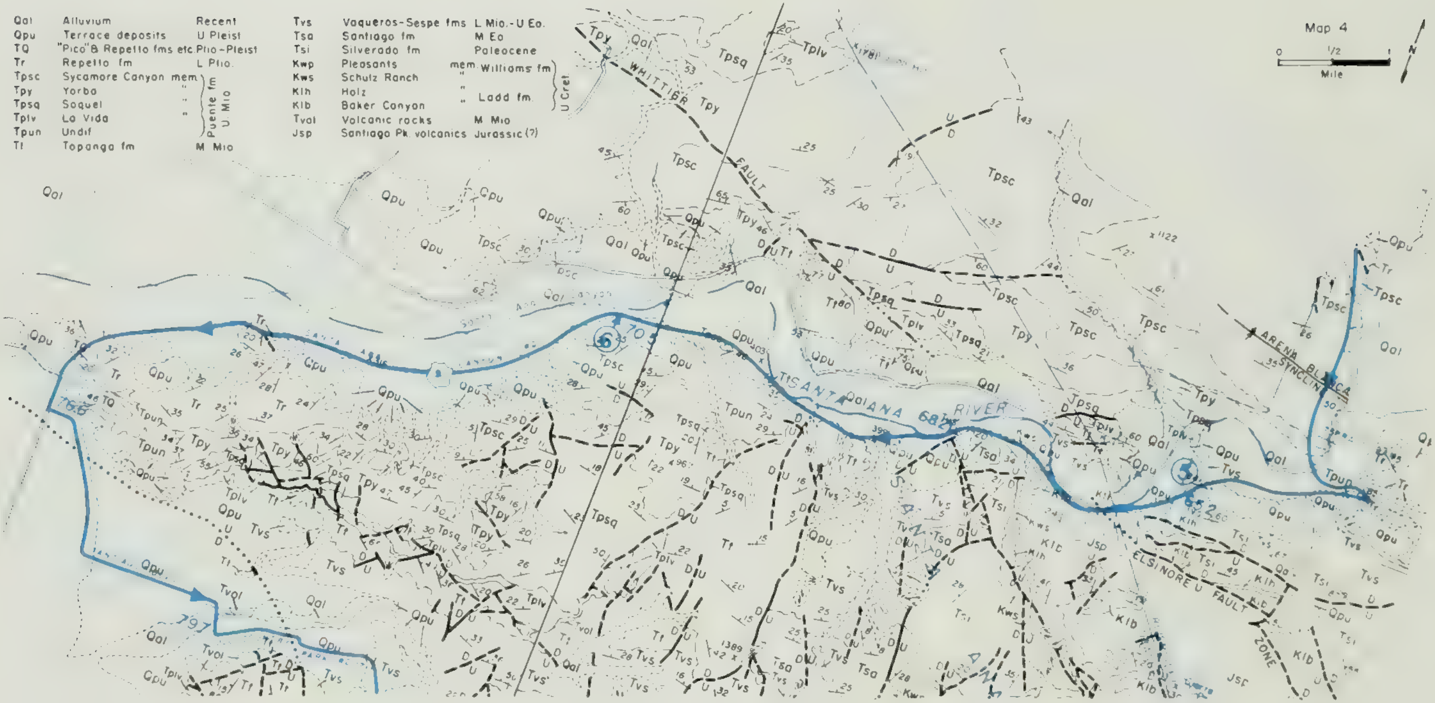
MAP 1. Downtown Los Angeles to Whittier.



Map 2. Whittier to Brea and Brea Canyon.



Map 3. Brea Canyon Road, Pomona to Prado Dam.



Map 4. Santa Ana Canyon and western Santa Ana Mountains.

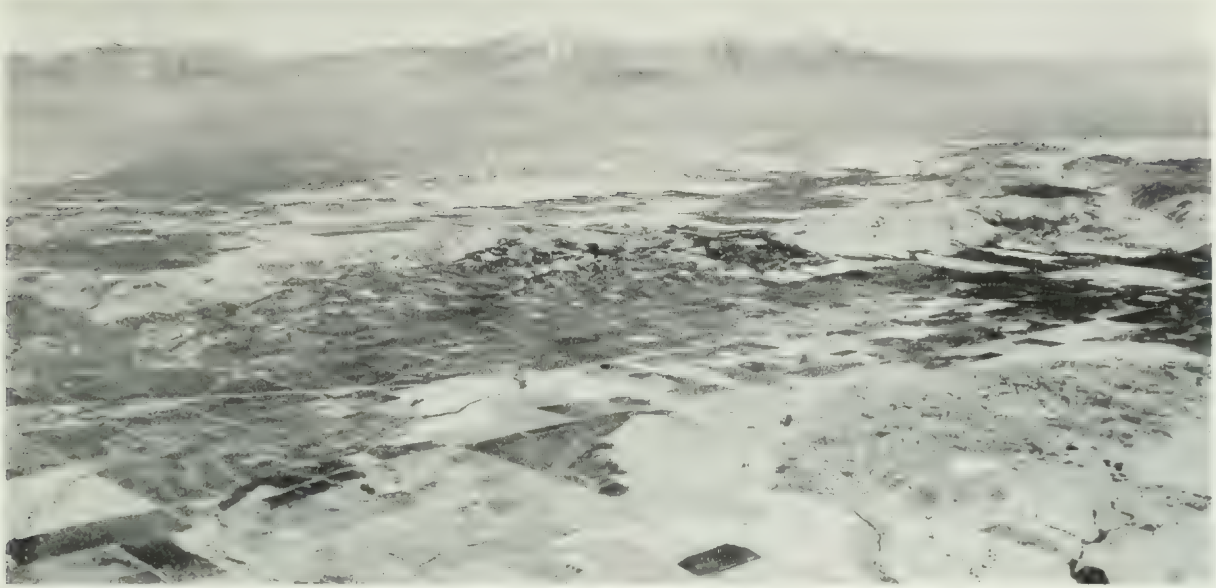


FIGURE 9. Air view northeastward from a point above Buena Park. The West Coyote oil field is at lower right. The Puente Hills extend across the center of the view, and Brea Canyon is at the extreme right. The high peak in the distant San Gabriel Mountains is San Antonio Mountain (Old Baldy Peak), altitude 10,059. *Pacific Air Industries photo.*

conglomerates are exposed in roadcuts farther south along State Highway 71. The steep dips and greater degree of induration of the Pliocene sedimentary rocks distinguish them from Pleistocene strata of similar lithology.

Siltstone of the Sycamore Canyon member of the Puente formation, containing many limestone concretions, is exposed in roadcuts about a mile north of Prado Dam. The Arena Blanca syncline, a broad northwest-trending asymmetric fold, is traversed by the highway between Pomona-Rincon Road and Santa Ana Canyon. Both flanks of the syncline are well exposed, and show Sycamore Canyon strata overlain by Repetto sandstone and conglomerate (fig. 13). The axis of the syncline is crossed at a point approximately west of Prado Dam. The fold probably is truncated by the Chino fault east of the highway near the dam.

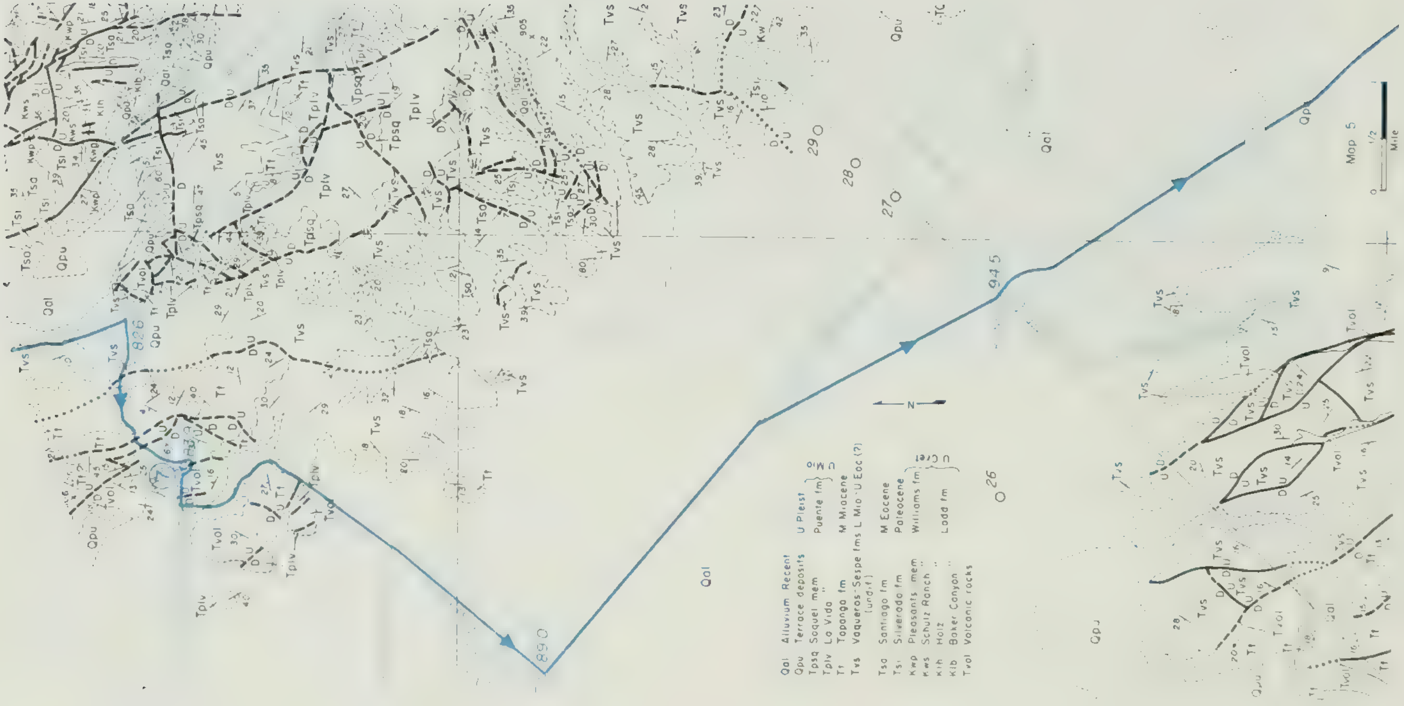
Santa Ana Canyon

The route down Santa Ana Canyon offers many features of geologic interest. It is best to proceed slowly for the next few miles, so that strata exposed in the numerous roadcuts can be identified with the aid of Map 4.

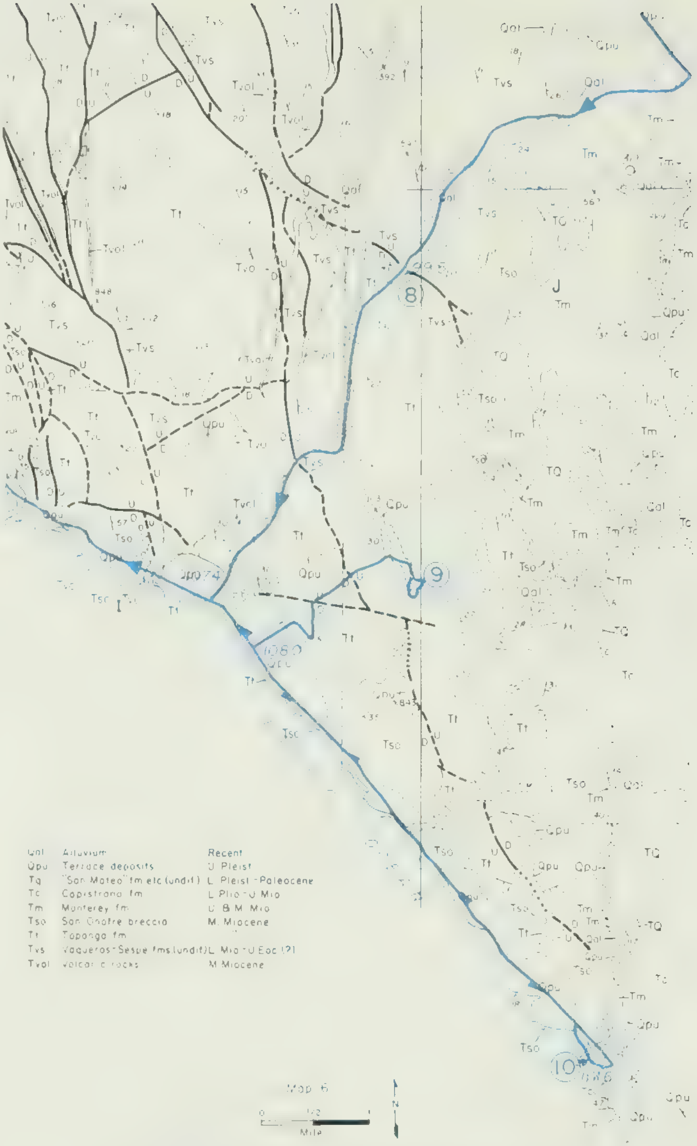
The Santa Ana River, which forms the geographic boundary between the Santa Ana Mountains and the Puente Hills, probably existed prior to their uplift, and maintained its course across them during Quaternary time. English (1926, p. 65) has noted that the course of this antecedent stream lies north of the core of hard metamorphic rocks of the Santa Ana Mountains, and has suggested that the river was forced to swing northward around this core.

The four members of the Puente formation, in ascending order, are the La Vida, Soquel, Yorba, and Sycamore Canyon. These are present on the south flank of the Arena Blanca syncline in the southeastern Puente Hills, but have not been differentiated south of Prado Dam where the Puente (upper Miocene) rocks are only 1,000 feet thick. Several stream terraces, developed on the Puente formation south of Prado Dam, are clearly preserved.

Between Prado Dam and Stop 5 the observer travels southwest along State Highway 18, through successively older rocks ranging



MAP 5. Western Santa Ana Mountains to San Joaquin Hills.


Qal Alluvium Recent
Qpu Terrace deposits U Pleist
Tq "San Mateo" fm etc (undif) L Pleist - Paleocene
Tc Capistrano fm L Plio - U Mio
Tm Monterey fm U & M Mio
Tso San Onofre breccia M Miocene
Tt Topanga fm
Tvs Vaqueros - Sespe fms (undif) L Mio - U Eoc (?)
Tvol volcanic rocks M Miocene
8
9
10
Map 6
0
1/2
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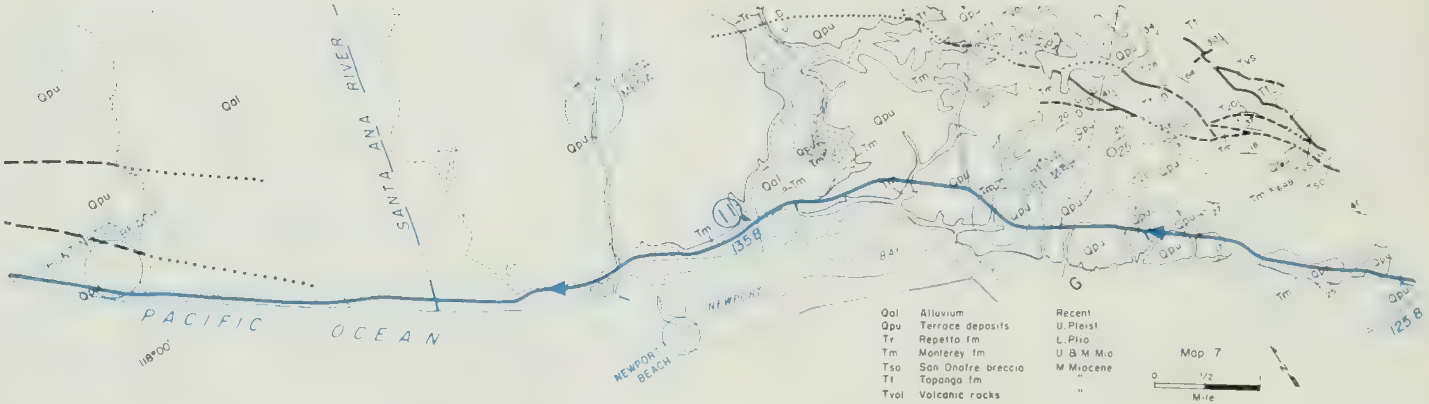
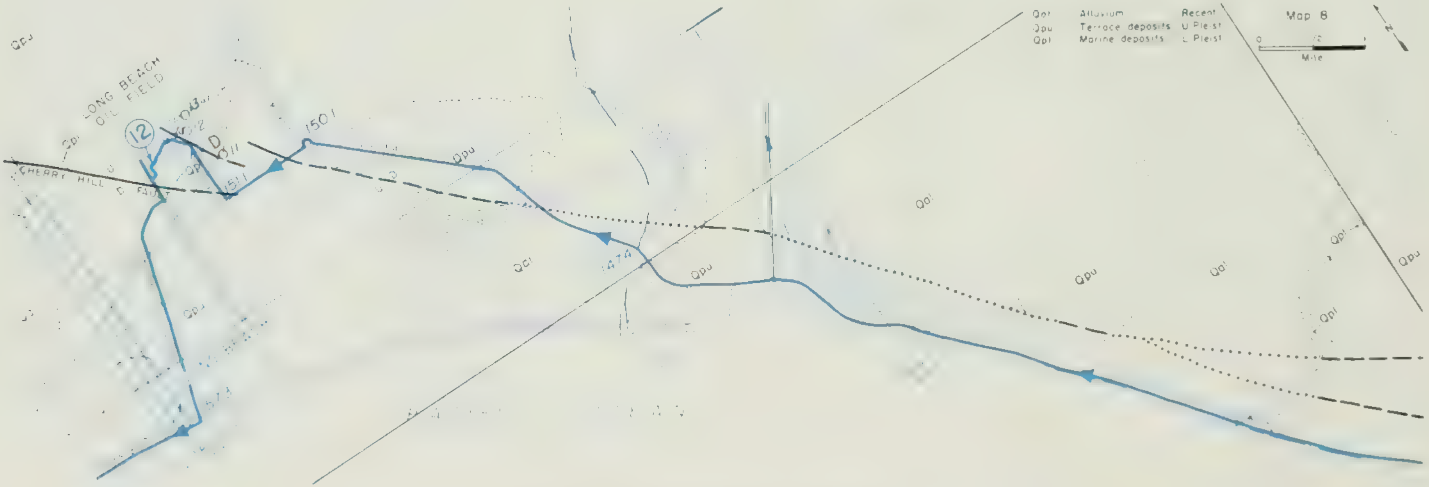
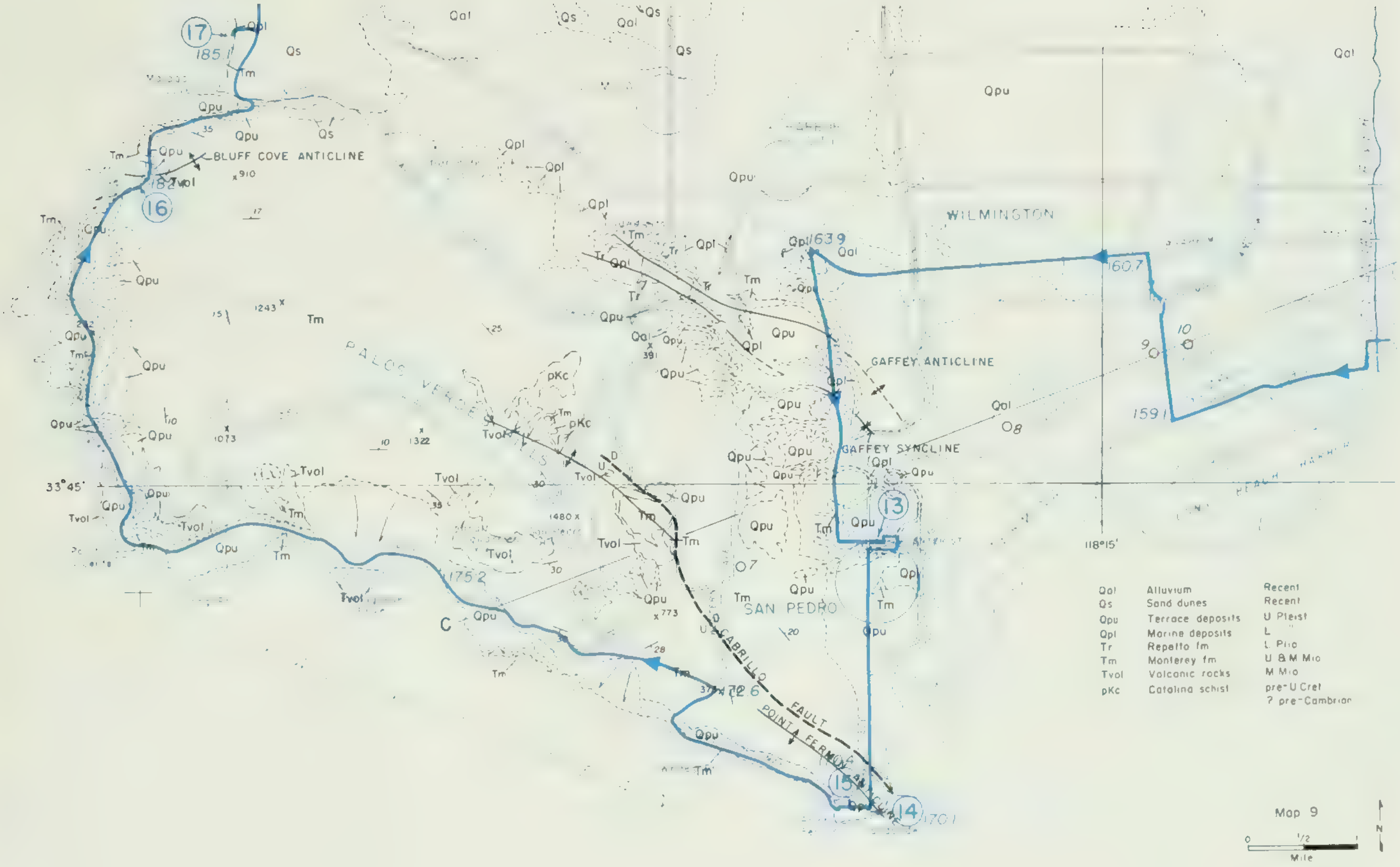
Map 6. San Joaquin Hills, Laguna Beach and vicinity.



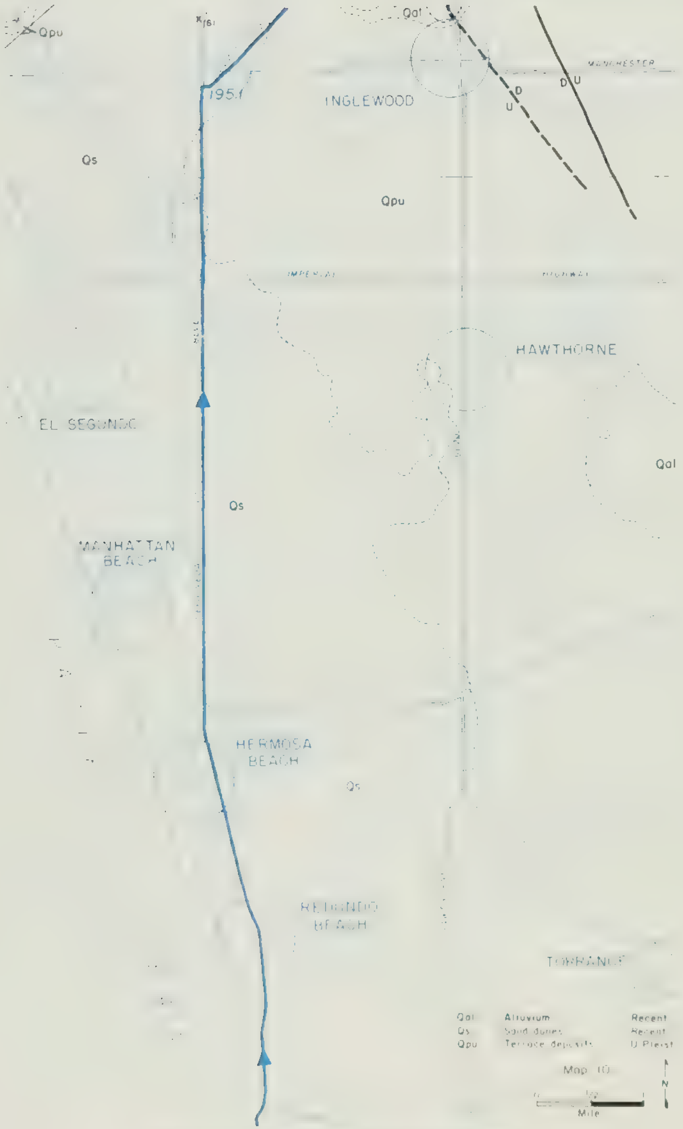
Map 7. Laguna Beach to Huntington Beach.



Map 8. Huntington Beach to Long Beach.



Map 9. Palos Verdes Hills.



Map 10. Palos Verdes Hills to Inglewood.

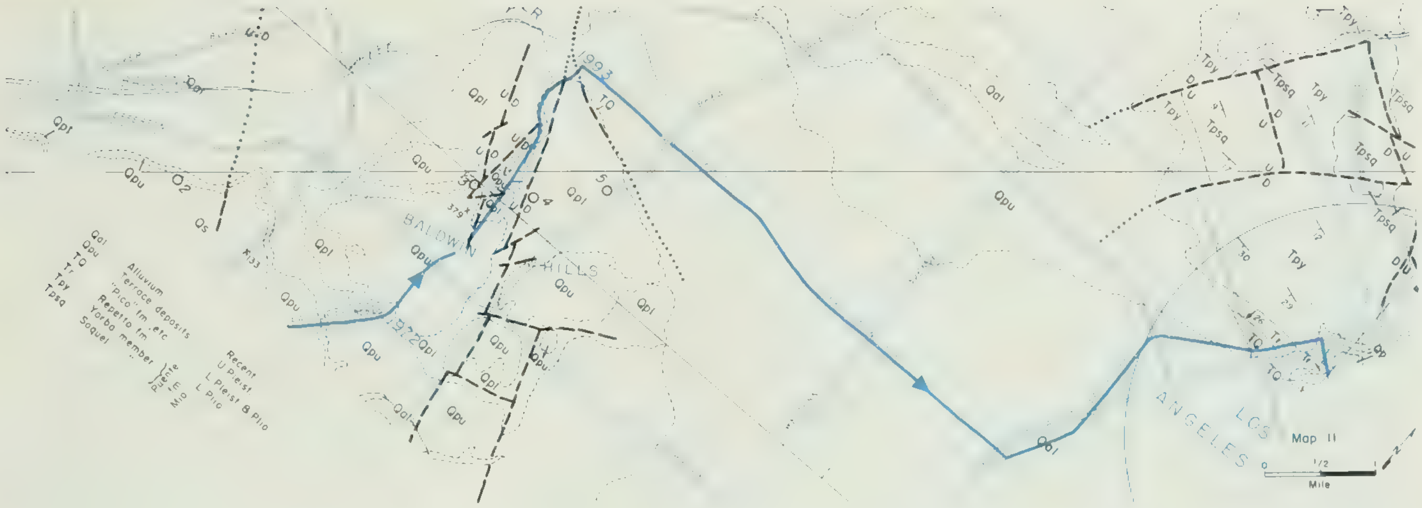
in age from Pliocene to Paleocene. At Stop 5 [65.2] locally overturned conglomerates of the Sespe formation (Oligocene ?) are in contact with finer-grained clastic rocks of the Silverado formation (Paleocene). About half a mile farther southwest along the road the Silverado formation in normal attitude is faulted down against strata of the Holz siltstone and Baker Canyon conglomerate members of the Ladd (Upper Cretaceous) formation (fig. 13).

Many details of the local terrain can be seen from Stop 5. Scully Hill, west across the river, is underlain by La Vida shale. In the small canyon north of the hill, the Soquel sandstone has been dropped down on the north along a fault (fig. 14). South of Scully Hill the Topanga (middle Miocene) sandstone underlies La Vida shale and is in turn underlain by the Sespe (Oligocene ?) formation. Still farther south of Scully Hill, basement rocks of the Santiago Peak (Jurassic ?) volcanics form a shallow, flat-topped mound that is flanked by Quaternary alluvium. These rocks are part of a landslide mass derived from the flat area near the crest of the hills to the southeast (left above the road). Slivers of Holz shale and Silverado formation are exposed beneath landslide debris of the Santiago Peak volcanics south of the highway. Only a thin wedge of the undisturbed Santiago Peak volcanic rocks is exposed along the road, although this formation is much thicker to the south (Map 4). Older rocks in this area, chiefly metasedimentary strata of the Bedford Canyon (Triassic) formation, occur higher in the Santa Ana Mountains.

Stop 5 is near the southeast end of the known extent of the Whittier fault. Displacement here is many thousands of feet, perhaps including about 15,000 of strike slip and several thousand feet of dip slip with downthrow to the north. The Elsinore fault, which extends southeast through the Peninsular Ranges more than 120 miles, is aligned with the Whittier fault near the Santa Ana River. The relationship of the two faults is not clear, and their connection has not been definitely demonstrated. The Whittier fault is concealed beneath alluvium of the Santa Ana River between Stop 5 and the notch west of Scully Hill. The southeasternmost exposure of the fault in the Puente Hills can be observed from Highway 18. It appears just to the left of a small barren cut above an orange grove 1 mile west of Scully Hill.

Continuing westward along Highway 18, the observer traverses successively younger units of a nearly complete sequence of Tertiary strata. In general, they form the south flank of a broad west-trending syncline whose axis essentially underlies the Santa Ana River.

Quaternary stream-terrace deposits are common on benches that have been cut into the Tertiary rocks at several levels along the Santa



Map 11. Inglewood to Los Angeles.

Ana River. At mile 68.2 an exceptionally thick and well-cemented, very gently dipping coarse conglomerate of Pleistocene (?) age is exposed in a steep roadcut.

Clay, mined in the Santa Ana Mountains from red and mottled beds within the Silverado formation, is stored in loading bins near the highway. From here it is transported to Los Angeles.

At Stop 6 [70.5], the Sycamore Canyon member of the Puente formation is made up of northwest-dipping graded beds, 1 inch to 6 feet thick. Individual beds commonly are coarse sandstone at the base and siltstone at the top. Biotite-rich layers are present just below the siltstones. The tops of the beds are rippled, and the coarsest part of the succeeding beds fills the ripples, but is smooth topped. The siltstones are commonly bent, broken, or shattered, and the breaks are filled by sandstone. The entire assemblage is interpreted as the product of turbidity currents flowing down steep slopes into deep waters.

Sharp folds in Repetto (lower Pliocene) strata are exposed in the roadcut [75.9] south of the turnoff to Olive. South of this exposure the Norwalk fault is concealed beneath the alluvium that flanks Burruel Ridge. The fault extends along the south flank of the ridge for about 2 miles, and thence trends southward through the low hills that flank the Santa Ana Mountains on the southwest (Maps 4 and 5). It flanks the Coyote Hills farther west. Sand and gravel are excavated for commercial use from Quaternary stream deposits along the south flank of Burruel Ridge.

Burruel Ridge to Laguna Beach

At Stop 7 El Modeno volcanics rest on strata of the Topanga (middle Miocene) formation and are overlain by the Puente (upper Miocene) formation. These volcanic rocks consist of flows, breccias, and tuffs. A basal flow is overlain by tuff breccia and palagonite tuff that in turn are capped by a basalt flow. El Modeno volcanics probably are correlative with the Glendora volcanics, and have been penetrated by some wells drilled in the eastern part of the Los Angeles basin.

For the next few miles the observer travels south across El Toro plain to the north flank of the San Joaquin Hills. The plain is the southeast end of the topographic lowland of the Los Angeles basin. To the east are the Santa Ana Mountains, whose anticlinal structure has been modified by intense block-faulting (see figs. 15, 16). The anticlinal axis is near Santiago Peak, about 16 miles east of Tustin. The San Joaquin Hills also are anticlinal with a northwest-trending axis. El Toro plain is grossly synclinal, but the subsurface structure is very complex.

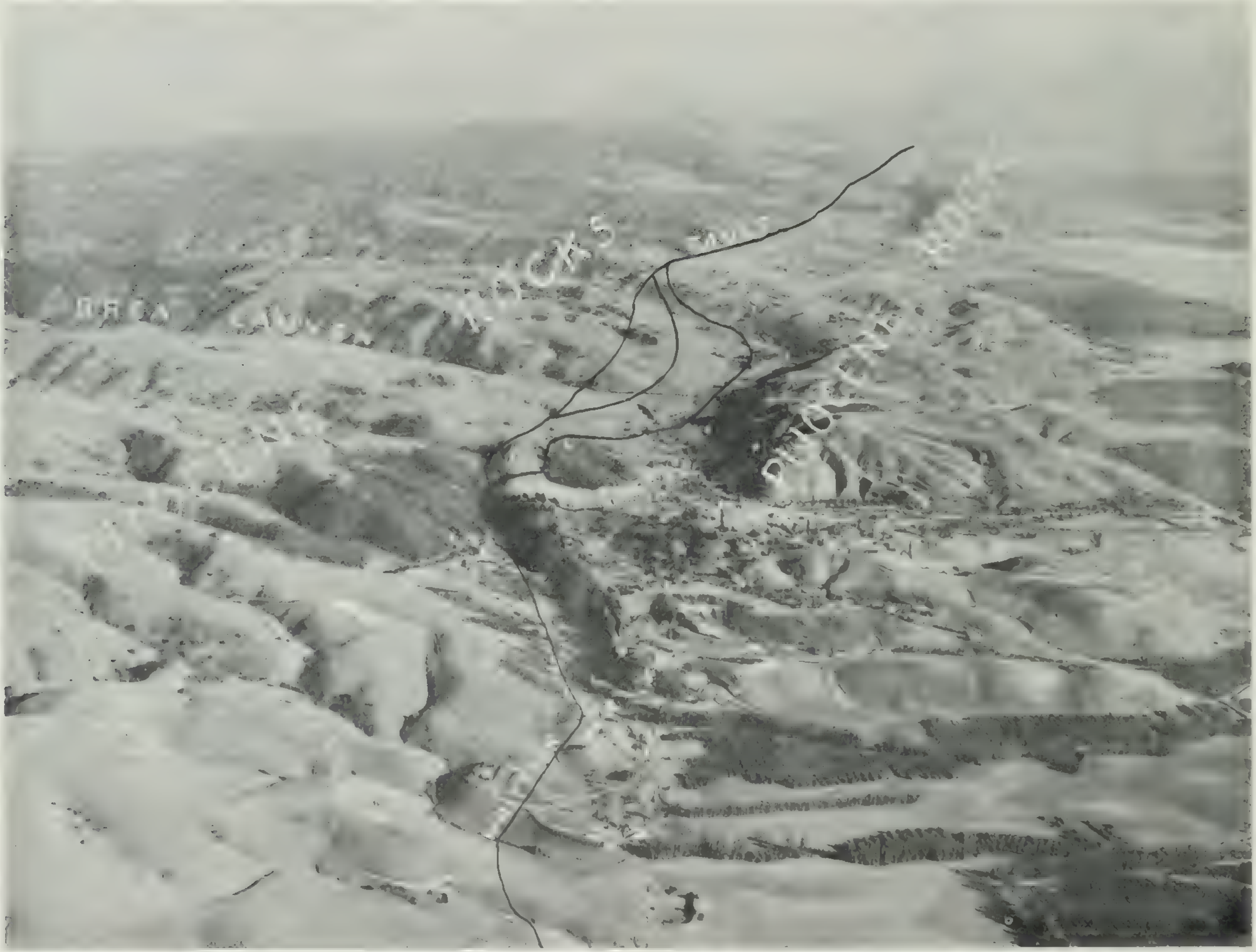


FIGURE 10. View east-southeast along the Whittier fault zone toward the Santa Ana Mountains. Miocene rocks crop out on the left, Pliocene rocks on the right. Apparent stream offsets indicate movement of the block on the right toward the observer. The dotted line indicates the route of the trip into Brea Canyon. *Photo by J. S. Shelton and R. C. Frampton.*

FIGURE 11. Structure section G-H through the Puente Hills east of Brea Canyon Road.

In the San Joaquin Hills (Map 6) Oligocene and lower and middle Miocene strata are broken into many blocks by faults active during middle Miocene time. Several of these faults have been occupied by volcanic dikes. The intrusive rocks ordinarily are more deeply weathered than the enclosing rocks, so that their outcrops are marked by slight depressions. The period of faulting was followed closely by deposition of strata of middle and upper Miocene age. Monterey (middle and upper Miocene) white diatomaceous shale, above the unconformity, and light-colored sandstone of the Vaqueros (lower Miocene) formation and red sandstone of the Sespe (Oligocene ?) formation, below the unconformity, are crossed along Niguel Road in the low rounded foothills on the northeast flank of the San Joaquin Hills. The two older formations are not differentiated on the map because they are in part intergradational, but they can be distinguished by the characteristic color of the major part of each formation. The sandstone of the Sespe formation generally weathers to form a somewhat rougher terrain than that underlain by the Vaqueros formation.

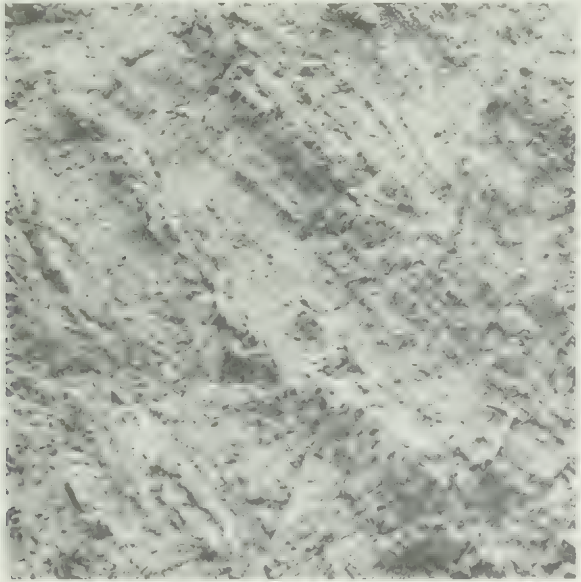


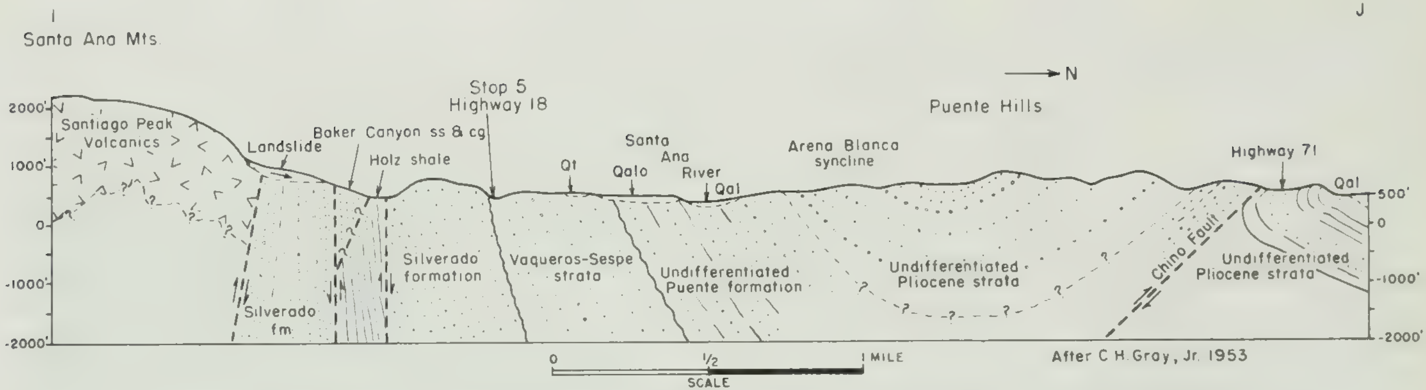
FIGURE 12. Flow banding in Glendora volcanic rocks (middle Miocene ?) on east side of highway, Stop 4, northern edge of Puente Hills.

At Stop 8 [99.5] Topanga (middle Miocene) sandstone and Sespe (Oligocene ?) strata are juxtaposed along faults that are overlapped by the Monterey (middle and upper Miocene) formation (see Map 6). The Monterey shale underlies rounded, grass-covered slopes east of Niguel Road. The strata of the Topanga formation lie unconformably beneath the slightly younger Monterey formation. They were faulted, tilted, and completely eroded from the northern (Vaqueros) block during the short time interval following deposition of the Topanga sandstone and preceding deposition of the Monterey shale.

Proceed to U. S. Highway 101 at Laguna Beach [107.8], turn left (east) to Thalia Street [108.4], follow it to Temple Hill Drive [108.9], and thence continue to the crest of Temple Hill.

From Temple Hill (Stop 9) one can look northward toward the low hills underlain by Miocene sedimentary rocks near Stop 8. Topanga sandstone also is exposed here, at the base of the nearest hill (fig. 17). It is overlain unconformably by the San Onofre breccia (brushy part of the hills to the east), which in turn is overlain unconformably by Monterey shale (grass-covered hills). The Miocene section is complete as compared to the section at Stop 8, where the San Onofre breccia has been overlapped by the Monterey shale. In general, the hills east of Temple Hill expose strata involved in the broad Capistrano syncline.

The Santa Ana Mountains rise high above El Toro plain northeast of Stop 9. Aliso Creek follows a deep canyon in the mountains, and extends across the south edge of the plain into a gorge through the San Joaquin Hills before emptying into the Pacific Ocean near South Laguna. It probably is an antecedent stream. Temple Hill and other flat-topped summits of the San Joaquin Hills are capped by



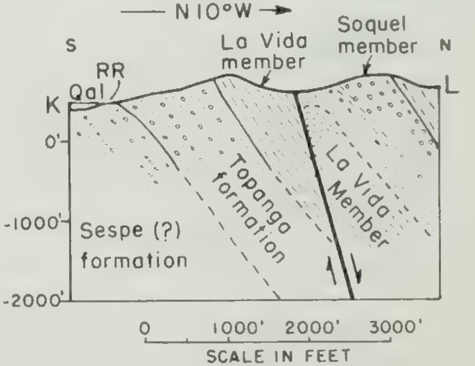
After C H Gray, Jr. 1953

FIGURE 13. Geologic section I-J through the eastern end of the Puente Hills and the northern part of the Santa Ana Mountains.

upper Pleistocene marine terrace deposits. In late Pleistocene time, therefore, the shore of the Pacific Ocean was northeast of the San Joaquin Hills. As those hills rose, in even later Pleistocene and Recent time, the course of Aliso Creek was extended southwestward, and the stream cut down through the rising anticline.

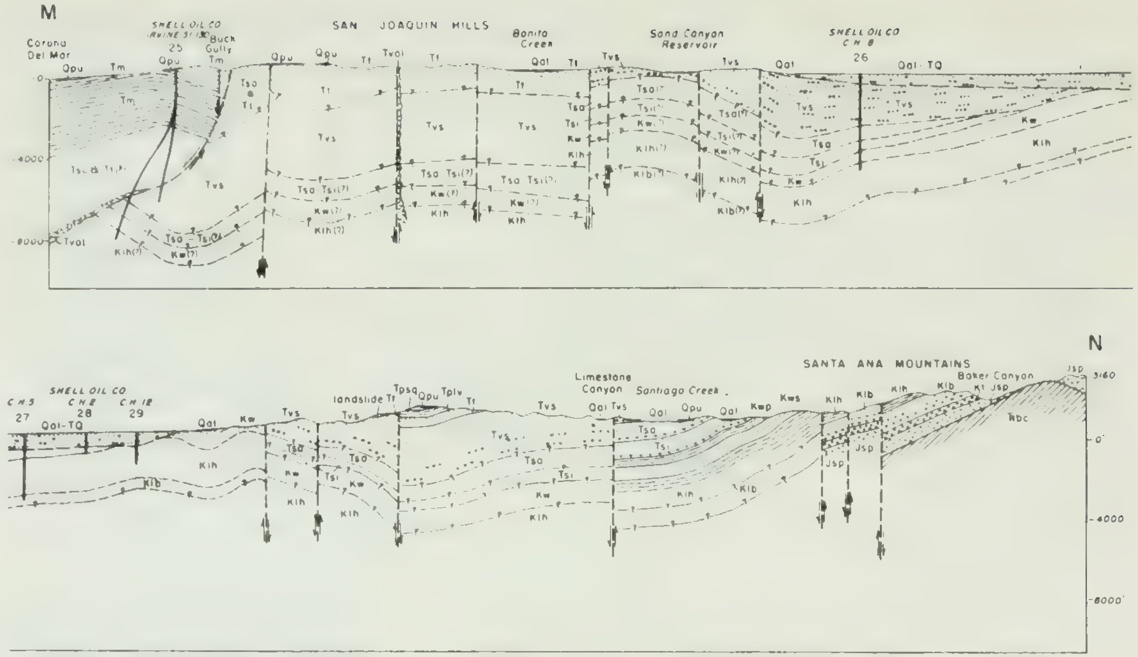
Return to U. S. Highway 101 alternate, and proceed left (east) to Stop 10.

The sea cliff between Laguna Beach and Salt Creek (Stop 10) is noted for its excellent exposures of the San Onofre (middle Miocene) breccia. This formation, which is uncommon elsewhere in the Los Angeles basin, consists of angular slabs, blocks, and chips of glaucophane schist and related schists embedded in matrices of two types; one gray and sandy, the other red, brown, or gray, and earthy. It circles the southeast nose of the San Joaquin Hills anticline just east of lower Aliso Creek, and also is exposed in a nearly continuous west-dipping belt extending from a point about 12 miles east of Laguna Beach southward to Oceanside, a distance of nearly 35 miles. The two outcrop belts flank the depression that marks the position of the Capistrano syncline. Rapid facies changes within the breccia unit are common. In the sea cliff southeast of Laguna Beach, about 2,500 feet of gray, white, and red sandstone, shale, grit, and breccia is composed chiefly of blue or green amphibole schist and related schists of the Catalina type in fragments that range in size from small flakes to slabs several feet in diameter. The contrast with other conglomerates and breccias of the region is emphasized by the absence of quartz-bearing plutonic rocks. Schists of the Catalina type are characterized by the abundance of albite and the presence of glaucophane, crossite, and lawsonite in metamorphic facies of the Franciscan group (Jurassic ?). These rocks include a complex of albitic, amphibolic, and chloritic schists, quartz schist, serpentine, and other rocks that are exposed over half of Catalina Island and in a small area in the Palos Verdes Hills. They are not known to crop out northeast of the of the Newport-Inglewood fault zone.

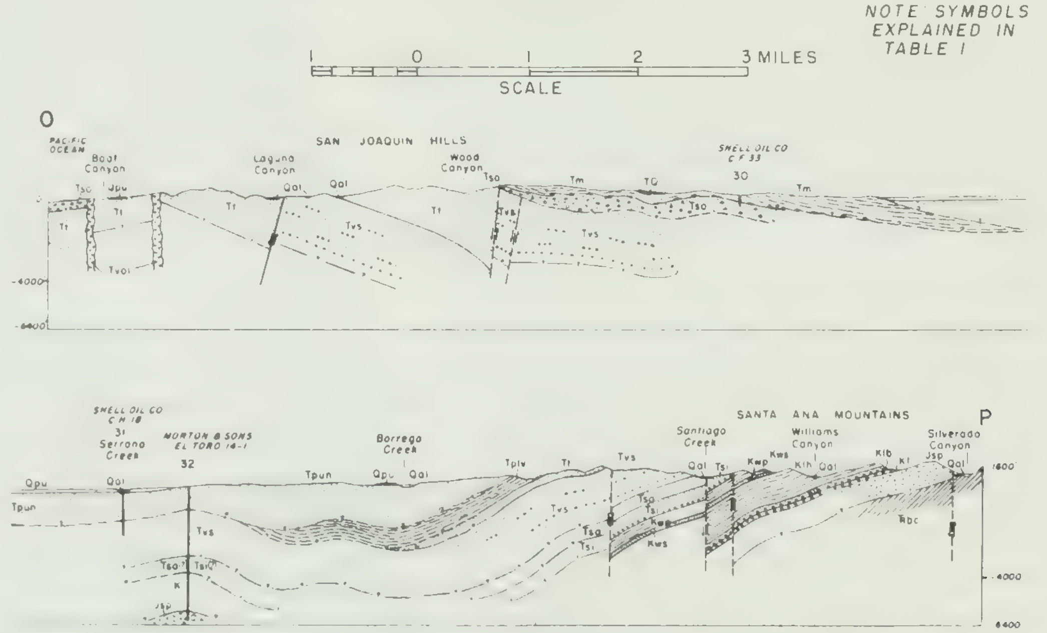


After Woodford, Shelton and Moran, 1944

FIGURE 14. Geologic section K-L through Scully Hill west of Stop 5, Santa Ana Canyon.



STRUCTURE SECTION M-N CORONA DEL MAR TO BAKER CANYON



STRUCTURE SECTION O-P, LAGUNA BEACH TO SILVERADO CANYON

FIGURE 15. Structure section M-N, Corona del Mar to Baker Canyon, southeastern Los Angeles basin. FIGURE 16. Structure section O-P, Laguna Beach to Silverado Canyon, southeastern Los Angeles basin.

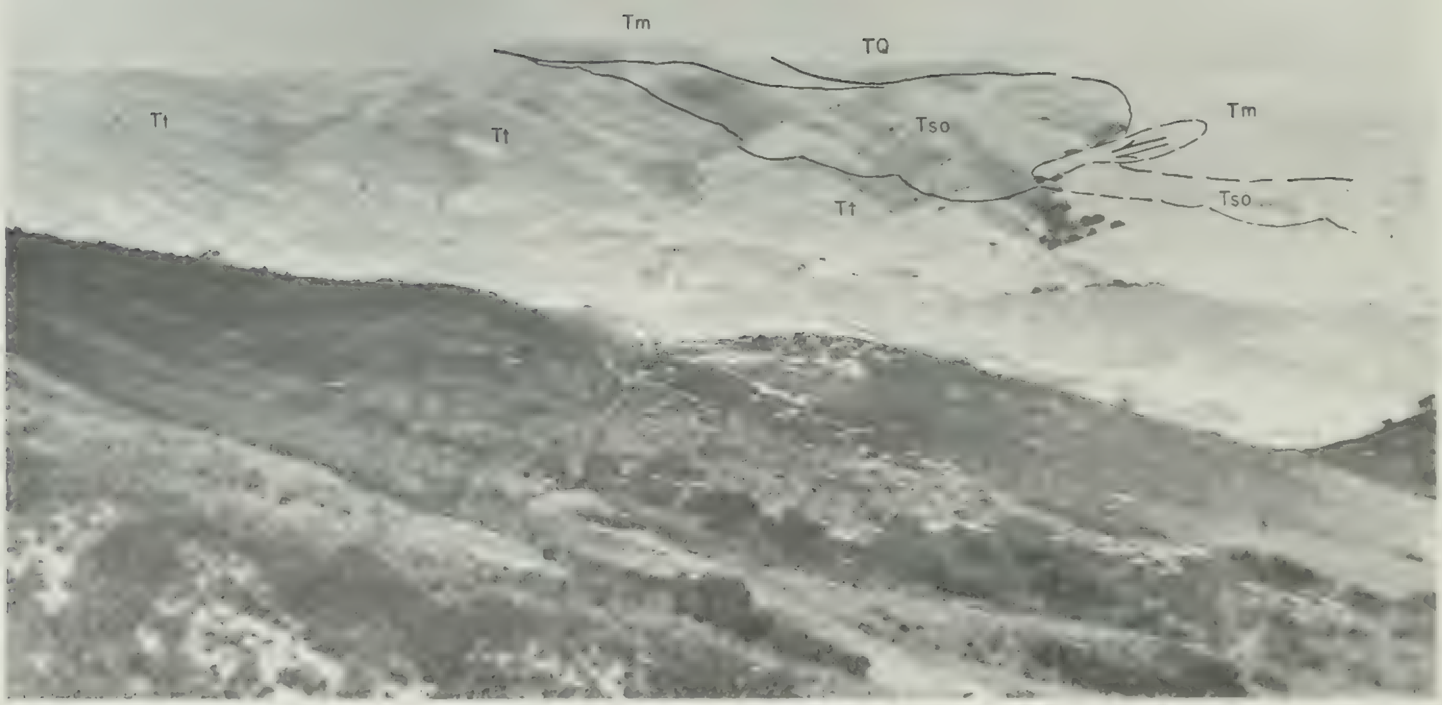


FIGURE 17. View northeast from Temple Hills near Laguna Beach, California. *Photo by R. F. Yerkes, Dec. 8, 1953.*

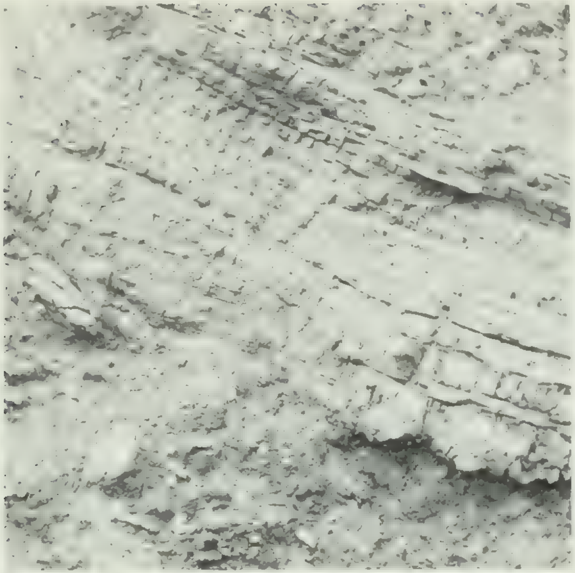


FIGURE 18. Close view of east-dipping Monterey shale overlying San Onofre breccia along sea cliff west of Salt Creek (Stop 10).

Woodford (1925, pp. 237-238) suggests that during middle Miocene time, a high and steep-fronted landmass of crystalline rocks extended from Newport Beach to Oceanside, slightly seaward from the present shoreline. A belt of piedmont alluvial fans, which bordered this landmass on the east, is partially preserved as the San Onofre breccia. The eastern extent of the breccia was probably marked by mud flows laid down following torrential cloudbursts. A nearby shore subjected to continual subsidence is postulated as the site for deposition of the marine sandy phase of the breccia.

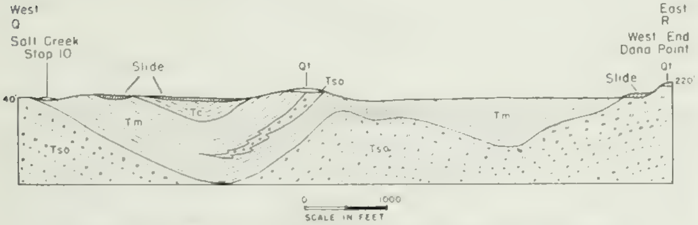


FIGURE 19. Section Q-R along beach, Salt Creek to Dana Point.

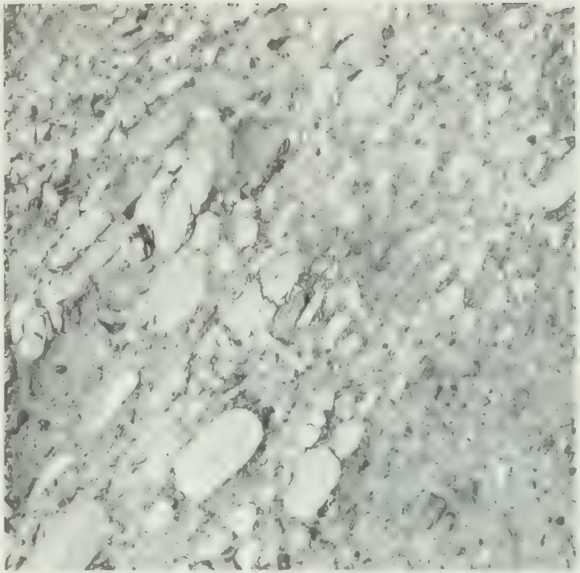


FIGURE 20. Detail of breccia of San Onofre type on wave-cut bench along shore southeast of Salt Creek. Angular fragments are composed of glaucophane schist and related schists.

Stop 10, on Salt Creek Road, is west of the axis of the Capistrano syncline. At the mouth of Salt Creek east-dipping San Onofre breccia is overlain by Monterey shale (fig. 18). Farther east, along the sea cliff, the Monterey shale is overlain by dark gray micaceous shale of the Capistrano (Mio-Pliocene) formation (fig. 19). Detail within the Capistrano formation is obscured along the sea cliff by a landslide mass. Still farther east, west-dipping Monterey shale is exposed in the east limb of the fold. A lens of breccia and sandstone of San Onofre type (fig. 20) may have been emplaced by submarine sliding, although the beds are not graded and the coarse clastic sediments have been washed clean and partially cemented with calcite. Pleistocene terrace deposits unconformably overlie the Tertiary rocks.

Return to Laguna Beach and continue westward along the Coast Highway.

Laguna Beach to Palos Verdes Hills

Three low peaks that are prominent along the coast west of Laguna Beach are composed of middle Miocene basalt that intrudes Topanga sandstone. At Abalone Point (Map 7), well-developed

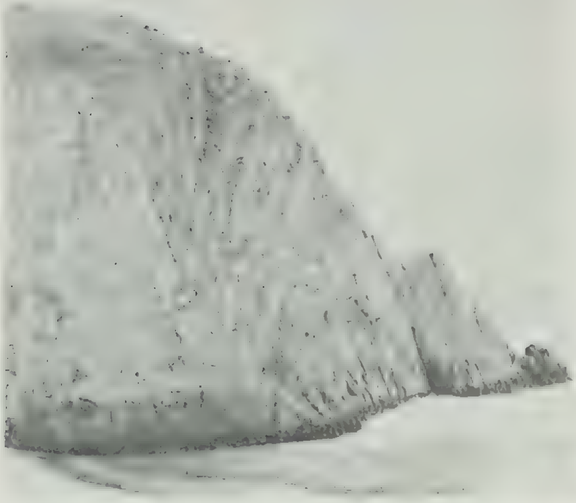


Figure 21. Columnar jointing in middle Miocene basalt at Abalone Point, 2 miles northwest of Laguna Beach.

columnar jointing is particularly evident in one dike (fig. 21) that can be seen from vantage points along the highway [125.8].

Gently dipping shales of the Monterey and Topanga formations underlie the broad terraces between Laguna Beach and Newport Beach. The several levels of terraces developed on the western slopes of the San Joaquin Hills are most plainly seen from points west of the hills.

Shallow folds in the Monterey shale are exposed in cliffs along the Newport Bay estuary. The Miocene strata are overlain by unusually fossiliferous Pleistocene marine sand, silt, and gravel. Immediately west of the overpass, west of Newport Bay [133.8], oil-saturated shale and siltstone of the Monterey formation are unconformably overlain by fossiliferous lower Pleistocene marine strata (fig. 22, Stop 11).

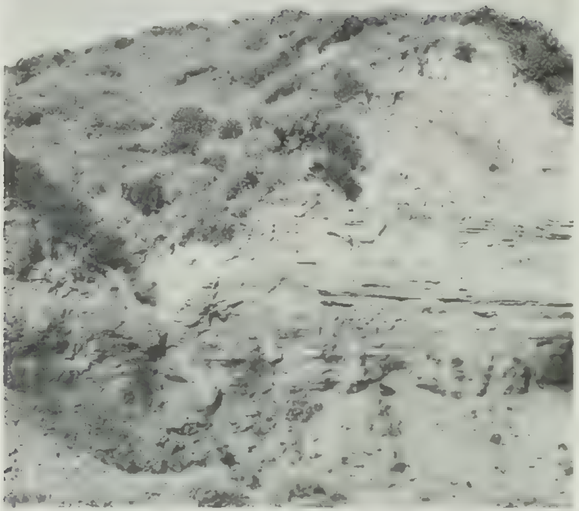


Figure 22. Fossiliferous lower Pleistocene sand (light colored) resting unconformably upon oil-saturated Miocene shale (dark) west of Newport Beach along north side of U. S. Highway 101 Alternate.

From Newport Beach to Long Beach (Maps 7 and 8) the observer travels parallel to the Newport-Inglewood fault zone, which extends from Newport northwestward at least as far as Inglewood. The fault zone is of economic importance because large reserves of petroleum are trapped in folds along it. It is of geologic interest because it is one of the principal fracture zones that traverse the Los Angeles basin. It is a deepseated fault zone, probably separating basement rocks of contrasting types. It has been the locus of movements that have extended into historic times. The basement fault (or faults) is represented in the overlying thick mantle of sediments by a series of faulted anticlines en echelon, each the site of an oil field and shown as such on figure 6.

The surface features along the Newport-Inglewood fault zone, such as minor fault scarps and recently formed anticlinal hills, can be observed at several stops along the remainder of this route. The topographic prominences related to the Newport-Inglewood fault zone overlie closed anticlines or more complex structures that contain oil pools.

Newport Oil Field. The Newport oil field, situated west of Newport Bay on the Newport Mesa, is the southeasternmost oil field along the Newport-Inglewood fault zone. Three separate fields are within the limits of the Newport oil field, the Newport Beach field, the Mesa field, and a new offshore field discovered December 14, 1953. This new oil field is the first to be found since the tideland areas were assigned to the State in 1953. The discovery well yielded 250 barrels per day from sands of probable late Miocene age at a depth of 4,445 feet, about 1,200 feet offshore.

The Newport Beach and Mesa fields (Parker, 1943, pp. 332-334) occupy an area of about 7 square miles. They are underlain by Quaternary sands that rest unconformably upon upper and middle Miocene and upper Pliocene strata, also in unconformable relationship to each other. The accumulations of oil are in Miocene strata. Subsurface structural interpretations indicate that the principal closures are against faults beneath stratigraphic overlap of Miocene beds, or on the crest of a broad, northwest-plunging anticline. Oil-saturated sandstone dikes and sills in upper Miocene and upper middle Miocene rocks complicate the interpretations of stratigraphy and structure. An unconformable contact between Pliocene and Miocene strata is exposed at the surface 2 miles northeast of the field, and slightly tilted sands of early Pleistocene age rest unconformably on strata of Tertiary age along the bay and on the south face of the mesa.

Between Newport Beach and Huntington Beach, the route crosses an extensive marshland that flanks the Santa Ana River. It is an erosional feature cut into the coastal mesas by the river at a time of lowered sea level.

Huntington Beach Oil Field. The Huntington Beach oil field, another of the major fields along the Newport-Inglewood uplift, is divisible into four areas (Weaver and Wilhelm, 1943, pp. 329-331), each of which is underlain by a separate structural trap. The Old area lies farthest inland, and is underlain by a northeast-dipping homocline truncated by a thrust fault that dips to the southwest; the Main Street area is underlain by a northwest-trending asymmetrical anticline; the Surf area is underlain by a homocline closed on the southwest by a fault that trends parallel to the main Huntington Beach fault; and the Townsite-Tideland area is underlain by an asymmetrical dome whose long axis is parallel to the coastline and lies about a quarter of a mile offshore.

The section includes about 700 feet of Pleistocene sand and gravel, 2,700 feet of Pliocene shale and sandstone, and an undetermined thickness of Miocene shale and sandstone. Middle Miocene rocks were encountered in one well at a depth of 9,054 feet; basement rocks have not been penetrated.

Oil is recovered from several zones in Pliocene and Miocene strata, the most productive being in the Tideland pool of the Townsite-Tideland area. Wells tapping the Tideland pool are closely spaced in long rows that border the north side of the Pacific Coast Highway west of the older fields of Huntington Beach. Drilling and servicing equipment is moved from well to well along tracks laid in a continuous concrete mat. The wells have been drilled at low angles to bottom sites situated as much as 4,800 feet offshore, and, in order to attain proper subsurface spacing and to avoid previously drilled holes, the courses of new holes are charted before drilling. In usual practice each new hole is confined to a pre-determined cylinder of ground whose radius is 50 or 100 feet. After a slightly deflected hole is drilled to a depth of 600 to 750 feet, its course is changed to a smooth transition curve at the rate of from 2½ to 3 degrees per 100 feet until the angle calculated to reach the bottom-hole location has been attained; the hole is then finished with a straight course at a uniform deflection angle. Several wells have deflection angles greater than 60 degrees from the vertical at measured depths of approximately 4,500 feet. One well course remained inside a cylinder of 50-foot radius from surface to bottom (about 4,500 feet), and was less than 20 feet away from the planned bottom-hole location.

Seal Beach Oil Field. The Seal Beach oil field (Map 8) lies mostly within the flood plain of the San Gabriel River between Alamitos Heights and Landing Hill, two low hills above the Newport-Inglewood fault zone (fig. 23). Petroleum has accumulated in several zones in lower Pliocene and upper Miocene strata between depths of 4,750 and 5,650 feet. Approximately 3,200 feet of rocks of Miocene age has been penetrated (Bowes, 1943, p. 325). These rocks are successively overlain by 2,500 feet of lower Pliocene strata, 2,900 feet of upper Pliocene strata, and 500 feet of lower Pleistocene strata. The principal structural feature is an anticline whose axis is parallel to the

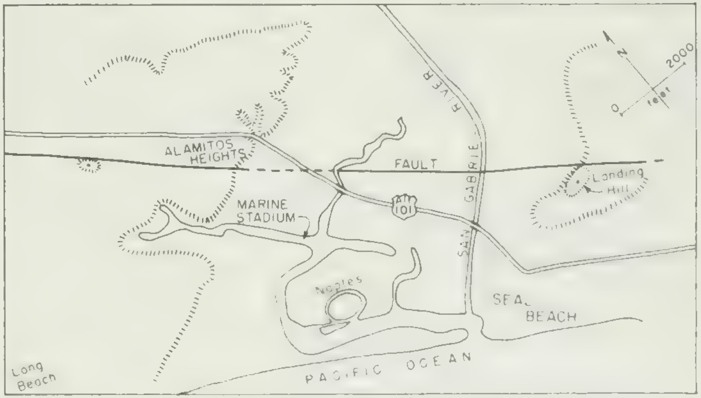


FIGURE 23. Sketch of antecedent channel of the San Gabriel River across the Newport-Inglewood zone of uplift at Seal Beach.

north-northwest trend of the Newport-Inglewood zone of uplift. The northeast limb of this fold is truncated by a fault.

Subsurface structures are reflected by the topography of the area. Alamitos Heights and Landing Hill, 80 feet and 60 feet elevation respectively, are remnants of a warped surface produced by episodes of late Quaternary folding. The folding is characteristic of the uplift along the Newport-Inglwood fault zone, which began in late Tertiary time and has continued to the present. Hillslopes developed on lower Pleistocene sediments are nearly parallel to the attitudes of the strata, which indicates that folding has occured in post-lower Pleistocene time. The San Gabriel River is antecedent, and has maintained a wide floodplain during the latest period of uplift (fig. 23).

The route of travel from the Seal Beach oil field to the Long Beach oil field is via Pacific Coast Highway parallel to the Newport-Inglewood fault zone. One mile west of the traffic circle turn right (north) on Temple Avenue to Hill Street. On the northeast corner of this intersection is the discovery well of the Long Beach oil field. This well, Shell Oil Company's Alamitos No. 1, was completed March 23, 1921, with an initial flow of 590 barrels per day, and is still operating.

Proceed northward to Panorama Drive, thence west around the north crest of Signal Hill to 23rd Street. From Panorama Drive one can see across the Los Angeles lowland area to the hills that border it on the north and east. Dominguez Hill, the site of the Dominguez oil field, is on the Newport-Inglewood uplift 5 miles northwest of Signal Hill.

Long Beach Oil Field. The Long Beach oil field (Stolz, 1943, pp. 320-324), originally known as the Signal Hill field, has yielded nearly 800 million barrels of oil from some 1,300 wells in an area of only 1,400 acres. The average yield of 530,000 barrels per acre is probably the highest of any oil field in the world. The close spacing of the wells in this field is the result of drilling permitted on town lots.

Signal Hill is one of the most pronounced topographic features along the Newport-Inglewood uplift. From its top, the early Spaniards are said to have signaled ships at sea. It is the surface expression of a narrow asymmetrical anticline that trends northwest. The position of the anticline is best shown by the distribution of the oil wells. The surface strata dip about 45 degrees on the northeast flank, and probably are steeper near faults in the subsurface. Dips are gentler on the southwest flank of the fold.

Pleistocene strata, about 1,500 feet thick at the apex of the fold, are underlain successively by 1,750 feet of upper Pliocene shale and sandstone and by 1,850 feet of lower Pliocene sandstone and shale. More indurated Miocene strata lie beneath the Pliocene strata either unconformably or transitionally. Miocene sandstone, siltstone, and shale extend to a total depth of about 15,000 feet.

Deep drill holes have penetrated Catalina-type schist at 10,509 feet on the northeast side of the Cherry Hill fault (Map 8 and fig. 5) and at 14,700 feet on the southwest side of this fault, which indicates a wedge of basement rocks in the anticlinal core of Signal Hill. The wedge is bounded on the southwest by the Cherry Hill fault, and probably is bounded on the northeast by another (subsurface) branch of the Newport-Inglewood fault zone.

Downtown Long Beach and points to the west are best viewed from Panorama Drive at 23rd Street (Stop 12). The Wilmington oil field, in the Los Angeles harbor area, is marked by the oil derricks west of Long Beach. The Palos Verdes Hills, benched by numerous wave-cut terraces, are flanked to the north by the Torrance oil field. Santa Catalina Island is visible (on clear days) beyond the southeast end of the Palos Verdes Hills.

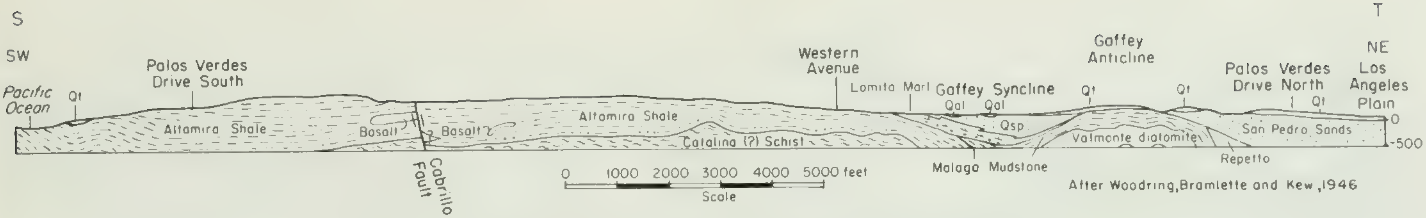
The Wilmington anticline, a subsurface feature of the oil field, was formed probably during mid-Pliocene time and shows practically no signs of rejuvenation during either of the episodes of marked uplift of the Palos Verdes Hills (late Pliocene and mid-Pleistocene), nor during mid-Pleistocene folding at Signal Hill.

West-dipping lower Pleistocene sand is exposed in roadcuts along 23rd Street between Panorama Drive and Cherry Avenue. The sand is bounded on the southwest by the Cherry Hill fault, which lies near the base of the ridge extending along the southwest limits of the oil fields. The terrace on the southwest slope of Signal Hill apparently was down-dropped along the fault.

To reach the Wilmington oil field and Los Angeles Harbor, proceed south on Cherry Avenue to 21st Street, thence right to Alamitos Avenue, and follow Alamitos Avenue through Long Beach to Ocean Boulevard. Follow Ocean Boulevard west across the Los Angeles River onto Seaside Boulevard and Terminal Boulevard beyond the drawbridge.

The Los Angeles River (Map 9), now confined to an artificial channel, has overflowed into the harbor area during periods of flood.

Terminal Island has been enlarged in recent years by filling in the area north of Seaside Boulevard. It is the site of several important installations, including the Naval shipyard south of Seaside Boulevard and the electrical generating plant of the Southern California Edison Company on the north side of the boulevard west of the drawbridge. Since 1937, the area underlain by the Wilmington oil field has been subsiding rapidly. The point of maximum subsidence, which now amounts to more than 18 feet, is slightly north of the Edison building. Since subsidence began, dikes have been constructed to pre-



After Woodring, Bramlette and Kew, 1946

FIGURE 24. Geologic section S-T across the eastern end of the Palos Verdes Hills.

vent parts of Terminal Island and adjacent parts of the mainland from being inundated, as many of the areas are now below sea level.

The rapid subsidence began in 1937, shortly after the start of exploitation of the Wilmington oil field. Horizontal surface displacements became noticeable a short time later. These generally involved the movement of points toward the center of the subsidence. The subsidence probably has occured mainly as a result of the lowering of hydrostatic pressure in subsurface strata (Gilluly and Grant, 1949). The horizontal displacements are a result of lengthening and movement of the surface as it is warped downward. It seems strange that only this field has been the scene of such rapid subsidence.

Proceed north (right) along the Terminal Island Freeway from Seaside Boulevard [159.1] to Anaheim Street, thence west (left) to Gaffey Street [163.9]. From the south ramp of Heim bridge one can see the difference in elevation between the sea water in Cerritos Channel and the surface of Terminal Island. This difference is most striking during periods of high tide.

Heim bridge, only recently constructed, already has subsided several feet. Pillars beneath the bridge have been lengthened to keep the structure in its proper position.

Wilmington Oil Field. The Wilmington oil field (Winterburn, 1943, pp. 301-305; 1952, pp. 19-22) has the highest annual production rate of all California oil fields, as of 1954. It has yielded nearly 50 million barrels per year for the past several years. Oil is recovered from six zones in Miocene and Pliocene strata and from one zone in schist-bearing conglomerate that lies on a basement of Jurassic (?) schist.

The field is on a well-developed northwest-trending anticlinal structure that overlies a subsurface ridge of crystalline basement rocks. Five north-trending faults with throws of 100 to 200 feet divide the field into six structural blocks which are themselves cut by numerous minor faults. The principal faults are normal faults, and with one exception they dip eastward. The amount of vertical displacement on these faults varies considerably, but in general the throw on a given fault is greatest near the crestal part of the anticline, and diminishes as the fault is traced outward toward both flanks. The faults act as barriers to the movement of fluids through the sands, and each of the structural blocks is distinguished by oil of a different gravity.

Geologic formations in the Wilmington field include basement rocks of Jurassic (?) schist, 4,100 feet of brown shale and sand of the Monterey (mostly upper Miocene) formation, 875 to 1,150 feet of gray and green shale, sandstone, and siltstone of the Repetto (lower Pliocene) formation, 1,000 feet of middle and upper Pliocene sandstone and siltstone, and 1,000 feet of Pleistocene and Recent sand, gravel, and clay.

The Torrance oil field is immediately northwest of the Wilmington field. It overlies the same basement ridge, and the two fields probably are connected by a productive structural saddle.

Palos Verdes Hills

General Features. The Palos Verdes Hills form an upland peninsula that is underlain mainly by marine sedimentary rocks of Miocene, Pliocene, and Quaternary age. These strata rest upon a basement of Catalina (Jurassic ?) schist, which crops out in a small area near the center of the hills. The hills are joined to the gently sloping lowland of the Los Angeles basin by a neck, about 7 miles wide, that is underlain by Quaternary alluvium. The topographic and geologic features of the peninsula resemble those of the islands off the coast of southern California, and during parts of Pleistocene time the hills evidently did form an island. The hills are of particular interest for evidence of late deformation provided by tilted lower Pleistocene beds and numerous well-developed upper Pleistocene terraces. The area also yields commercial quantities of diatomite and basalt and sand.

The structure of the Palos Verdes Hills is anticlinal, and is featured by the draping of Tertiary marine strata over a subsurface

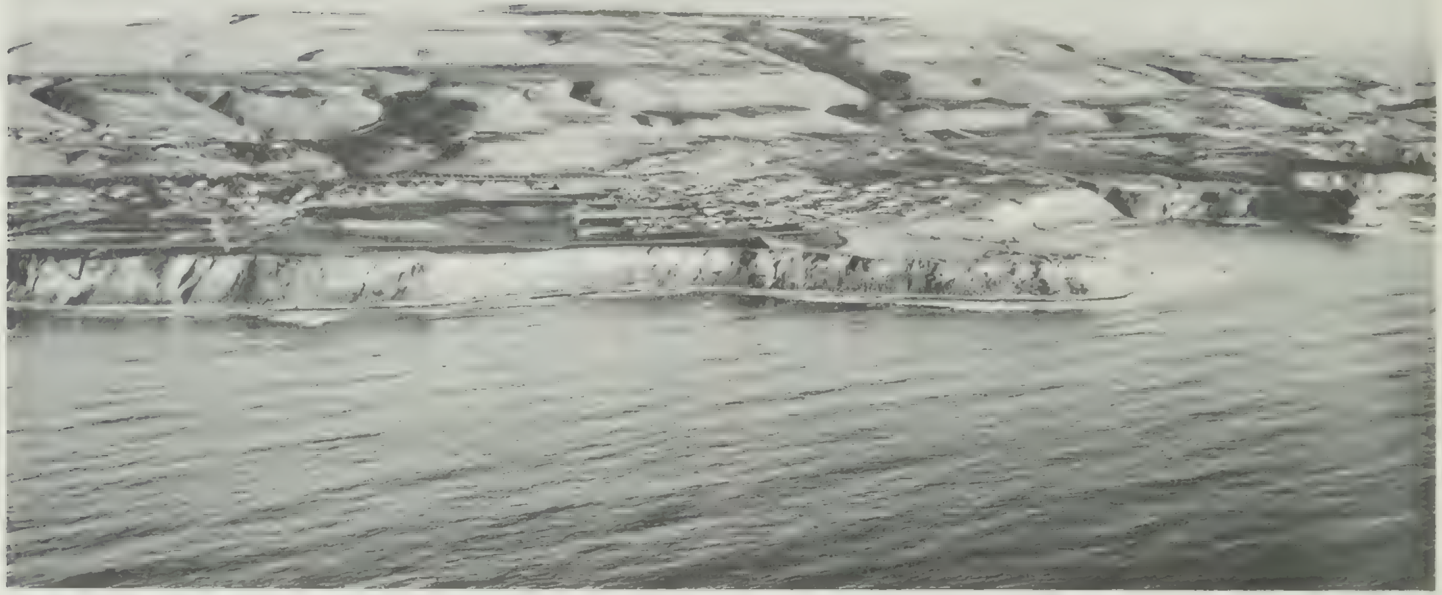
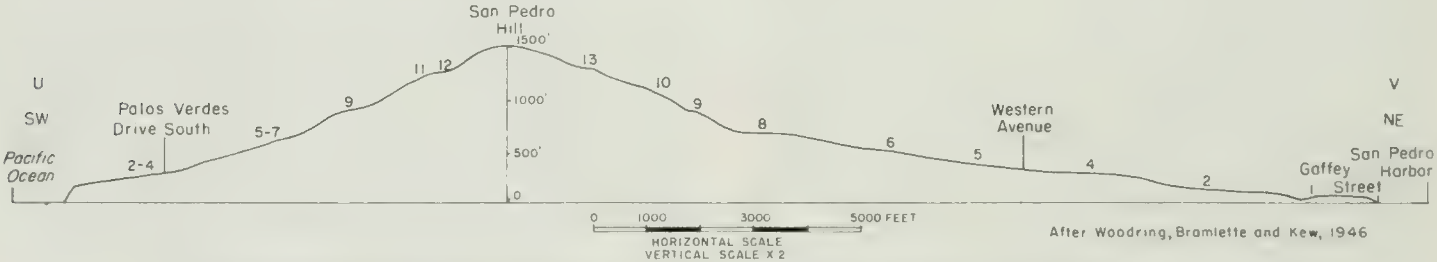


Figure 25. Aerial view of wave-cut marine terraces on western end of the Palos Verdes Hills, south of Malaga Cove. View is eastward across Palos Verdes Point, in foreground, toward San Pedro Hill, highest point in the hills. Stream channels were entrenched inland from the lowest exposed terrace in former cycles of erosion, and are being entrenched at the sea cliff at the present time. *R. C. Frampton photo.*



After Woodring, Bramlette and Kew, 1946

Figure 26. Marine terraced profile (section U-V) from Portuguese Bend to northern edge of San Pedro, Palos Verdes Hills.

ridge of Catalina glaucophane schist (fig. 24). The hills are bounded by a subsurface fault on the northeast, and probably by another fault that lies offshore to the south. The strongest folding of the sediments occurred in late Pliocene time, and was followed by lesser deformation in mid-Pleistocene time.

The principal marine terraces, 13 in number, range in altitude from sea level to 1,300 feet near the crest of San Pedro Hill (Map 9, figs. 25, 26). In general, they are best developed on the seaward side of the hills. The lowermost (youngest) terrace along the north slope of the hills has been deformed so that it is now barely recognizable.

The most thorough description and interpretation of the geological features of the Palos Verdes Hills are provided in U. S. Geological Survey Professional Paper 207 (Woodring, Bramlette and Kew, 1946). This publication is the source of most of the data presented in the following paragraphs, and should be consulted for additional information.

The geologic formations of the Palos Verdes Hills are shown in figure 27.

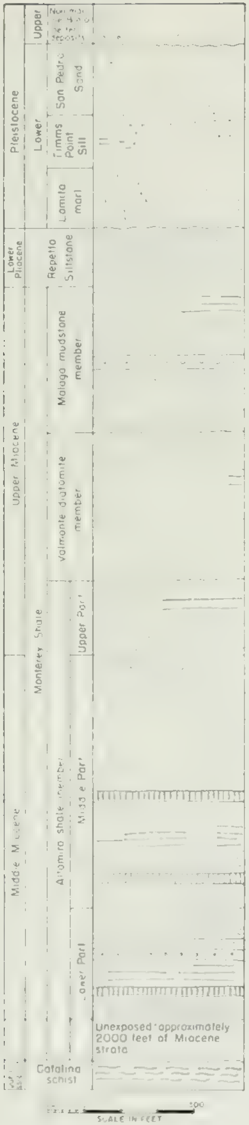


FIGURE 27. Generalized stratigraphic section in the Palos Verdes Hills.

Miocene Rocks. Miocene rocks underlie most of the Palos Verdes Hills area. The strata rest directly on Catalina schist, and overlap this much older terrane in a northward direction, the younger strata being on the north slope of the hills.

The strata are of middle to late Miocene age, and have been assigned to the Monterey shale, a formation name that is applied to organic and siliceous shales regardless of the stratigraphic position they occupy within the Miocene column (Woodring, Bramlette and Kew, 1946, p. 13). Shales of the Monterey type in the Santa Monica Mountains are included in the Modelo formation (upper Miocene), and those that underlie the Puente Hills and much of the Los Angeles basin are included in the Puente formation. Two thousand feet of Monterey shale is exposed in the Palos Verdes Hills, and an additional 2,000 feet may be present beneath the Point Fermin and Long Point areas.

The Monterey shale of the Palos Verdes Hills has been divided into three members. In ascending order, these are the Altamira shale, the Valmonte diatomite, and the Malaga mudstone. Basaltic rocks of middle Miocene age are intrusive into the lower and middle parts of the Altamira shale, but are not known to penetrate younger rocks.

The Altamira shale member consists essentially of a lower 275 feet of silty shale and sandy shale, a middle 400 to 675 feet of cherty shale, chert, and limestone, and an upper 100 to 300 feet of phosphatic shale and bituminous shale. Tuffaceous layers and lenses of conglomerate occur throughout the member. The Valmonte diatomite member, 300 to 500 feet thick, is mostly diatomite, diatomaceous shale, and diatomaceous mudstone. The Malaga mudstone member consists essentially of 300 to 600 feet of radiolarian mudstone.

The Altamira shale member is the most widespread of these units. Valmonte diatomite occurs locally along the crest of the hills and along parts of their northeast and east flanks. Outcrops of the Malaga mudstone are confined to small patches in and near San Pedro, along the north side of the hills, and at Malaga Cove, the type locality.

Pliocene Rocks. Rocks of Pliocene age in the Palos Verdes Hills are represented by 150 feet of siltstone assigned to the Repetto formation (lower Pliocene). Upper Pliocene sedimentary rocks are not present in the Palos Verdes Hills. The Repetto siltstone is exposed at Malaga Cove and at other localities near the north border of the hills, where it consists of soft, massive, glauconitic foraminiferal siltstone. The strata disconformably overlie the Malaga mudstone member of the Monterey shale, and are unconformably overlain by Pleistocene strata.

Pleistocene Rocks. Sedimentary rocks of Pleistocene age are exposed principally on the east and north flanks of the Palos Verdes Hills. The lower Pleistocene rocks have been divided into three units. In ascending order, these are the Lomita marl, Timms Point silt, and San Pedro sand. They are overlain unconformably by the Palos Verdes sand (upper Pleistocene).

The Lomita marl consists of 60 to 70 feet of calcareous rocks, principally marl and sand that include strata composed of granular calcareous organic remains such as shell fragments, Foraminifera, and Bryozoa (Woodring, Bramlette, and Kew, 1946, p. 43).

The Timms Point silt is composed of 30 to 80 feet of brownish, generally massive, sandy micaceous silt that apparently was swept across the Los Angeles basin from granitic areas to the north. It is the least extensive of the three units.

The San Pedro sand, the uppermost unit of early Pleistocene age in the Palos Verdes Hills, is 175 feet thick. It is composed of evenly bedded and cross-bedded sand with lesser amounts of gravel, silty sand, and silt. Large open pits on the north flank of the Palos Verdes Hills yield sand from this formation for industrial uses.

In central San Pedro the three lower Pleistocene units are present in succession, but elsewhere one or more of them commonly is missing. The San Pedro sand, however, is found wherever lower Pleistocene strata occur. The inferred relations of the Lomita marl, Timms Point silt, and San Pedro sand are illustrated in figure 28.

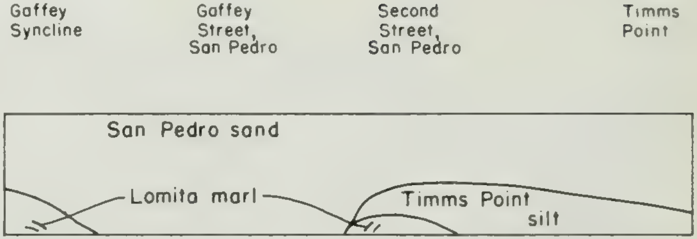


FIGURE 28. Inferred relations of Lomita marl, Timms Point silt, and San Pedro sand, San Pedro, California.

The Palos Verdes sand (upper Pleistocene) is a marine terrace deposit that rests unconformably upon lower Pleistocene strata. It occurs on the youngest (lowermost) terrace in San Pedro and in local areas on the north side of the Palos Verdes Hills. It ranges in composition from fine-grained gray sand to coarse-grained sand and gravel.

All of the terraces and terrace deposits are more or less completely covered by nonmarine alluvium and colluvium, mostly brown and earthy, and strikingly different from the clean gray marine sands.

Gaffey Street, San Pedro. South from Anaheim Street [163.9], Gaffey Street follows an ancient stream channel cut across the arched lower terrace. The stream channel was arched along with the crest of the Gaffey anticline, which underlies the belt of low hills that is crossed west of the Union Oil Company refinery. The depression south of the low hills is underlain by the Gaffey syncline (Map 9). Figure 24 illustrates the structure beneath this belt of Pleistocene deformation, which overlies the deep-seated Palos Verdes fault along the north flank of the hills. The Lomita marl (lower Pleistocene) on the south flank of the syncline thins northward and pinches out near the crest of the anticline. The San Pedro sand (lower Pleistocene) overlies the marl in the syncline, but rests upon Miocene shale on the north flank of the anticline.

Proceed south along Gaffey Street to Second Street, thence left (east) to Pacific Avenue.

Second Street, San Pedro. A complete sequence of marine Pleistocene strata was once exposed in cuts along Second Street between Pacific Avenue and Beacon Street, and the greater part of the section still can be seen between Pacific Avenue and Mesa Street (Stop 13, fig. 29). The lower Pleistocene units dip gently northeastward above an unconformable contact with the Malaga mudstone. Upper Pleistocene terrace deposits overlie all of the older units with distinct unconformity. The Malaga mudstone (upper Miocene), which dips gently northwest, consists of massive mudstone with lenses and concretions of limestone, and is associated with minor amounts of siltstone. The unconformity between the Malaga mudstone and the Lomita marl is present at the intersection of Pacific Avenue and Second Street.

Along Second Street (Stop 13, mile 167.0) the gently northeast-dipping Lomita marl is about 50 feet thick, and consists mostly of marl and calcareous sand (fig. 29). It is in turn overlain by a 78-foot thickness of Timms Point silt, which extends eastward to the intersection of Second Street and Mesa Street. The massive, yellowish brown silt contains a few fossiliferous layers that range in thickness from 6 inches to 2 feet. The San Pedro sand is exposed on First Street between Mesa and Center Streets. East of Mesa Street, on First Street, the San Pedro sand is overlain unconformably by the Palos Verdes sand (upper Pleistocene) and nonmarine terrace sand and gravel. The unconformity between the nearly horizontal upper Pleistocene strata (Palos Verdes sand and nonmarine terrace cover) and the Lomita marl and Timms Point silt, is marked by conglomeratic and fossiliferous sand along Second Street between Pacific Avenue and Center Street. Proceed south on Center Street to Third Street, thence right (west) to Pacific Avenue. Turn left (south) and continue to Stop 14 at the end of Pacific Street.

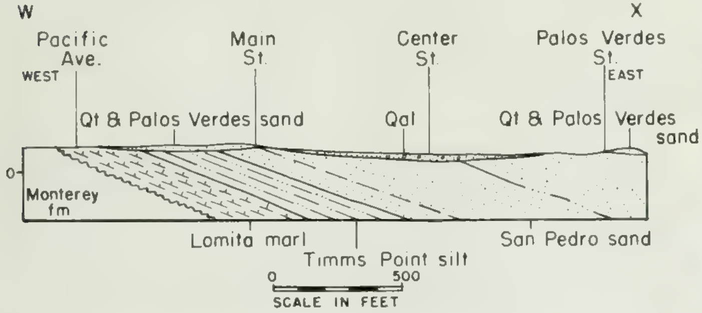


FIGURE 29. Section W-X along Second Street, San Pedro, California.

The three lower Pleistocene marine units extend as far south as Ninth Street at Mesa Street, where they are overlapped by terrace debris. At Timms Point, about half a mile farther southeast, the Lomita marl is 3 or 4 feet thick and lies between Timms Point silt and Malaga mudstone.

Point Fermin. The Point Fermin landslide mass can be seen from Stop 14, at the south end of Pacific Avenue. The movement of this mass began in the fall of 1929, and continued during 1940 and 1941. The landslide developed along the 100-foot sea cliff, and affected an area about 1,000 feet long that extends inland as much as 400 feet. Here the Altamira shale (upper Miocene) dips gently southward and seaward on the south limb of the Point Fermin anticline. The landslide occurred as a result of the slippery nature of the shale, its seaward dip, and the undercutting of the cliff by wave erosion. As the sliding progressed, the area was cleared of all habitants, buildings were removed, and roads were closed. A main fissure as much as 10 feet wide (fig. 30) and an irregularly fissured zone as much as 100 feet wide were created by the landslide. These fissures have been filled artificially with sand.

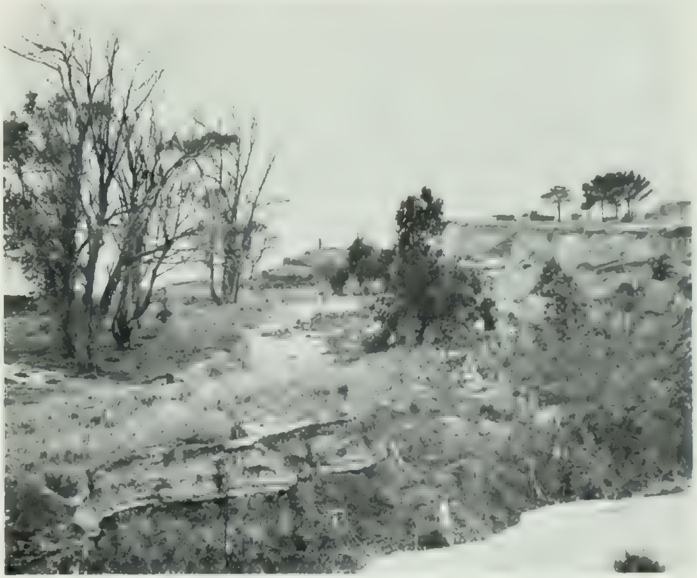


FIGURE 30. View westward across the Point Fermin landslide mass from the parking area at the south end of Pacific Avenue, San Pedro.

Point Fermin to Malaga Cove. From Stop 14, travel westward on Shepard Street to Paseo Del Mar, and along Paseo Del Mar to Western Avenue west of Whites Point. Follow Western Avenue northward for about half a mile, thence proceed west (left on Palos Verdes Drive South) around the coastal margin of the Palos Verdes Hills.

Bluish, schist-bearing sandstone of the upper part of the Altamira shale (upper Miocene) is exposed in the first roadcut along Paseo

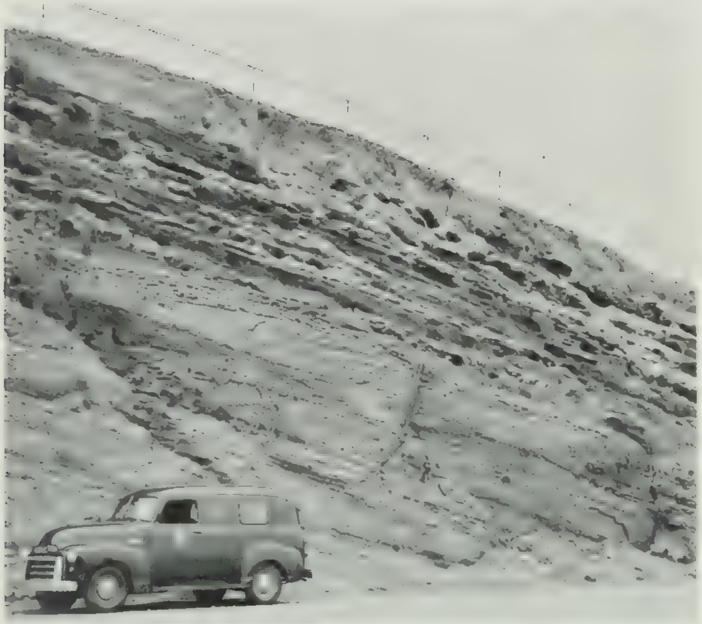


FIGURE 31. Bluish, schist-bearing sandstone of the upper part of the Altamira shale (upper Miocene) exposed along Paseo Del Mar (Stop 15) north of Point Fermin. Thin beds of brecciated Monterey shale appear in the upper part of the exposure. Pleistocene megafossils are preserved at the base of the overlying sediments near the top of the roadcut.

Del Mar [170.4] north of Point Fermin (Stop 15). These strata are composed of grains and flakes of glaucophane schist that probably were derived from nearby bedrock masses of Catalina schist. They are interbedded with tan siliceous shale and brecciated shale (fig. 31). The sandstone is similar to the sandy facies of the San Onofre breccia observed near Laguna Beach, and in these hills is restricted to the vicinity of Point Fermin, where it forms a fairly thick section.

Westward along Paseo Del Mar and Palos Verdes Drive are many features of scenic and geologic interest. Palos Verdes Drive is situated low along the south flank of the anticline of the Palos Verdes Hills. The area is underlain by south-dipping strata of the Altamira shale (middle and upper Miocene), which have been intruded by basaltic volcanic rocks and are overlain unconformably by upper Pleistocene terrace deposits. Unconformities between the shale and the various terrace deposits are best exposed in sea cliffs. Most of the route of travel between Point Fermin and Malaga Cove is along terrace number two (fig. 26), which is the second youngest, the best preserved, and probably the most extensive of the terrace group. At several places the road climbs as high as terrace number five.

Numerous sea cliffs afford exposures that illustrate the gentle dip of the Altamira shale toward the sea. Few beaches are present between the points, principally because ocean currents probably deposit sand farther north or because the sand is carried seaward in submarine canyons (U. S. Grant, pers. communication).

Wave-cut terraces on the south slopes of the Palos Verdes Hills are utilized for farming, chiefly for the growth of flowers and row crops.

Santa Catalina Island, 22 miles to the southwest, commonly is visible from many points along Palos Verdes Drive. The isthmus separating the northwest third of the island from the main portion is less than 50 feet above sea level. The northwest half of the island is underlain by Catalina schist of the glaucophane-schist facies. Miocene volcanic rocks make up the major part of the south half of the island. Soapstone deposits on the island were utilized by Indians for carving pottery, and several mines have yielded lead, zinc, copper, and silver intermittently since 1863. The island has been a popular resort area.

Santa Barbara Island, made up of Miocene volcanic rocks, lies 25 miles westward from the northwest tip of Santa Catalina Island. It can be seen on the horizon on very clear days.

Numerous bodies of middle Miocene basaltic rocks have been intruded into the lower and middle parts of the Altamira shale on the south and west slopes of the Palos Verdes Hills. They are exposed in roadcuts at Point Vicente and Bluff Cove.

Most of the basaltic rocks form sills that range in thickness from a foot to several hundred feet. Adjacent sedimentary rocks commonly have been baked in zones ranging in thickness from less than a foot to several feet. In many places both the basalt and the sedimentary rocks were brecciated during the intrusion. Sandstone dikes that contain basaltic debris are exposed in the sea-cliff north of Point Vicente.

The basalt generally has weathered dark brown and has been altered to a soft, powdery rock characterized by bright hues of yellow, pink, and lavender. The fresh rock is dark gray. Interstitial opal and cavity-filling dolomite, quartz, and barite are present in the basalt. The rock is quarried from several open pits east of the landslide at mile 175.2.

The largest landslide mass in the Palos Verdes Hills underlies Portuguese Bend [175.2]. Although several small landslide masses flank the route of travel along Palos Verdes Drive, they are not easily detected from the drive. The hummocky topography in the Portuguese Bend area delineates much of the landslide. The incom-

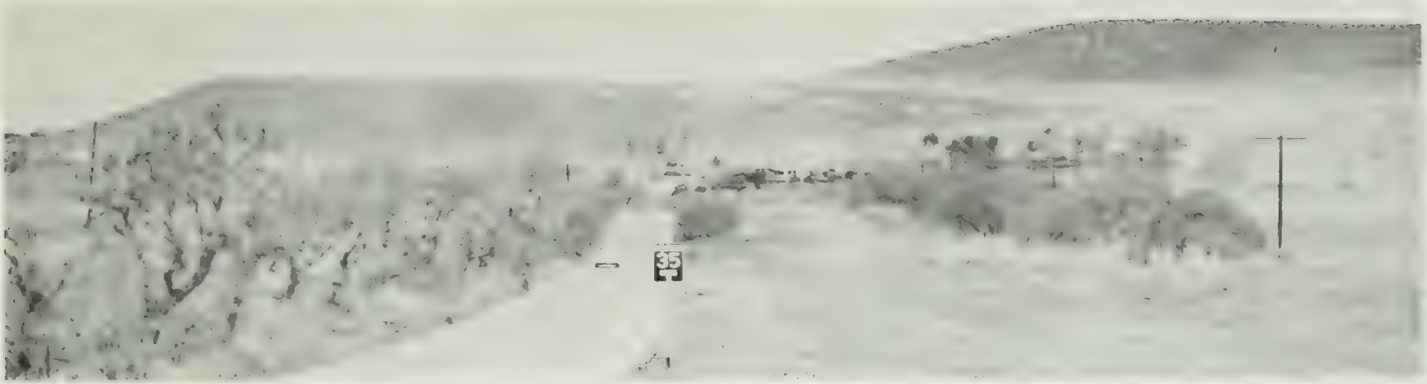


FIGURE 32. Steep-fronted wave-cut terraces on the northwest slope of the Palos Verdes Hills.

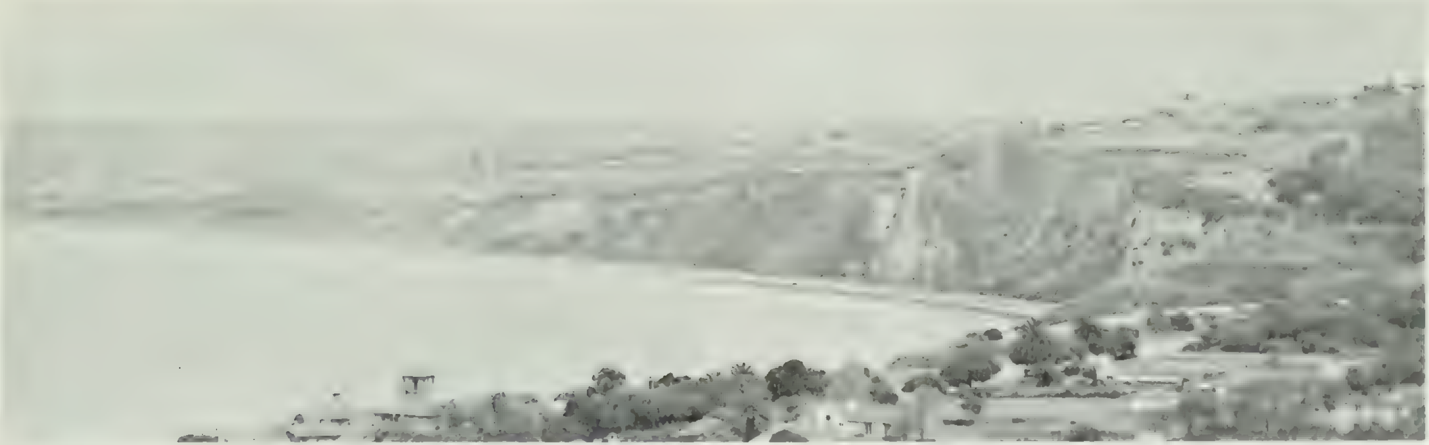
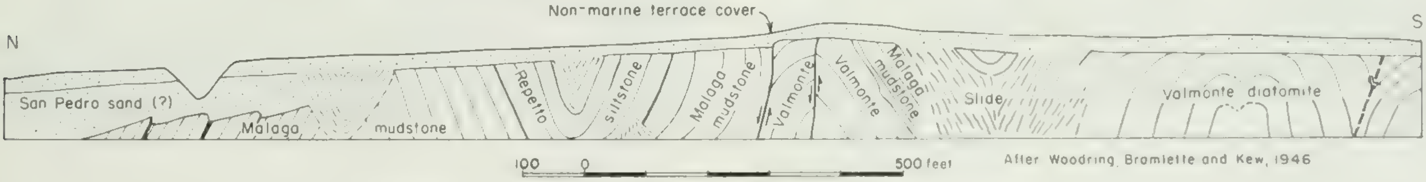


FIGURE 33. Sea cliff at Malaga Cove as seen from west end of Palos Verdes Estates. Steeply dipping Miocene and Pliocene strata are unconformably overlain by Pleistocene sand. Recent sand dunes form low hills along the beach beyond Stop 17.



After Woodring, Bramlette and Kew, 1946

FIGURE 34. Sea cliff at Malaga Cove, northwest end of the Palos Verdes Hills.

petence of the Altamira shale and the down-slope dip of the shale have induced movement of the landslide masses along water-soaked layers.

West of Portuguese Bend the observer passes the Wayfarer's Chapel [176.7], situated atop a small knoll north of Palos Verdes Drive. The sides and roof of the chapel are glass.

From the south limits of Palos Verdes Estates one can see two well-developed wave-cut terraces to the north (fig. 32). The faces of these terraces probably are the steepest of any that have been preserved in the Palos Verdes Hills.

At Stop 16 [182.1] are excellent exposures of basaltic rocks. Here the basalt forms a sill-like body lying between strata of the Altamira shale. Exposed in the roadcut is the intrusive contact, as well as weathered and unweathered surfaces of the basalt. The basalt and Altamira shale are folded in a gentle anticline that trends eastward from Bluff Cove.

In Bluff Cove, breccia that is similar to the San Onofre breccia in composition is exposed in the crestal part of the Bluff Cove anticline. These strata apparently are interbedded with Altamira shale, and have been uplifted between two faults.

Proceed through Palos Verdes Estates, thence north to Calle Miramar. Turn left (west) to Via Rivera and stop at the parking area at the public beach.

Malaga Cove (Stop 17). The sea cliff at Malaga Cove (fig. 33) lies athwart the belt of deformation that extends westward from San Pedro across the north flank of the Palos Verdes Hills and marks the position of the Palos Verdes fault. Here tightly folded Miocene and lower Pliocene rocks are overlain by nearly flat-lying strata of lower Pleistocene and Recent age, and are truncated by faults that trend west, or roughly parallel to the fold axes (fig. 34).

Approximately 200 feet of laminated diatomite and diatomaceous shale containing phosphatic stringers and nodules is exposed about 1,500 feet south of the north end of the cliff. These strata are a part of the Valmonte diatomite. They are conformably overlain by Malaga mudstone, which is mainly massive radiolarian mudstone or fine-grained siltstone about 325 feet thick. Phosphatic nodules and schist and quartz pebbles occur at the base of the mudstone member. The Repetto siltstone (lower Pliocene) disconformably overlies the Malaga, and consists of about 100 feet of soft, massive, glauconitic foraminiferal siltstone which is preserved in the syncline about 500 feet south of the north end of the cliff. A landslide has obscured details of the siltstone. Approximately 75 feet of sand and gravel of the San Pedro (?) sand and 25 feet of nonmarine terrace sand occur at the top of the cliff.

Deformation of Miocene strata was slight in this area prior to late Pliocene time, as indicated by the disconformity at the base of the Repetto siltstone. Strong deformation took place in late Pliocene time, however, as shown by the intense folding, faulting, and subsequent erosion of Repetto and Monterey strata before deposition of lower Pleistocene sand and gravel. The slight northward tilting of San Pedro (?) sand indicates mild deformation during late Pleistocene time (fig. 35).

Return to the main road and proceed north (left). At Elena Avenue cross to U. S. Highway 101 Alternate and proceed north to La Tijera Boulevard [195.1], thence right (northeast) to La Cienega Boulevard [197.2], thence left (north) through the Baldwin Hills.

Malaga Cove to the Baldwin Hills

Sand carried inland by a prevailing west wind forms a 10-mile ridge of dunes that extends between the Palos Verdes Hills and

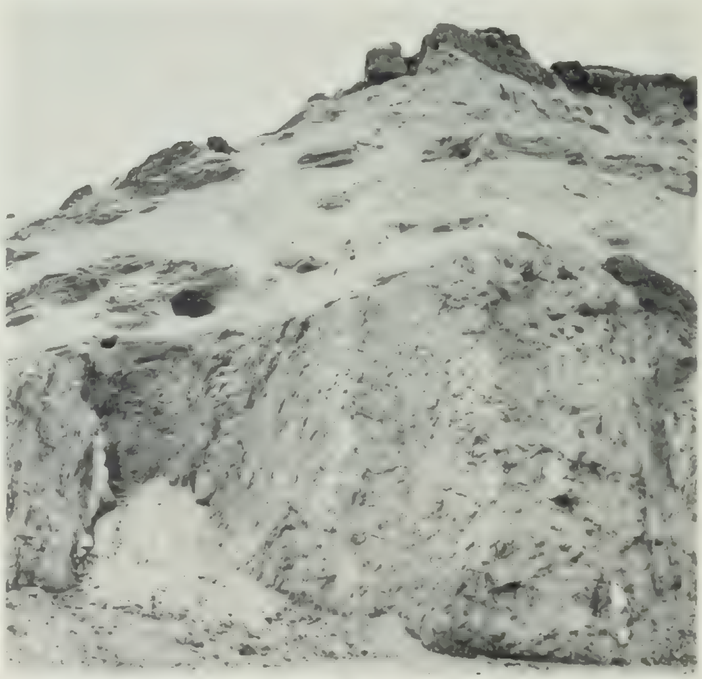


FIGURE 35. Nearly vertical Malaga mudstone (middle and upper Miocene) overlain by gently north-dipping San Pedro (?) sand (lower Pleistocene) near north end of Malaga Cove.

Playa del Rey (Map 10). The youngest dunes are nearest the sea, and are very steep-sided in places. The older dunes lie farther inland, and are now stable and topographically more subdued.

The part of Los Angeles basin southwest of the Newport-Inglewood fault zone is underlain by basement rocks composed of Jurassic (?) schist, the surface of which is marked by ridges and valleys. The oil fields southwest of the Newport-Inglewood fault zone are underlain by folds draped over the ridges in the basement rocks.

Oil has accumulated in the folds as a result of up-dip migration, and is recovered in several fields southwest of the Newport-Inglewood fault zone. Locally (see table 2) oil has migrated from the Miocene strata into fractured schist, and is recovered from the schist in commercial quantities.

Baldwin Hills

The Baldwin Hills (Map 11) are the most prominent of the hills that overlie the Newport-Inglwood fault zone, and also are the northwesternmost topographic feature along this uplift. The hills are approached from the south across a south-sloping plain that probably represents a segment of a late Pleistocene land surface. This surface now culminates at the crest of the hills at an altitude of 513 feet.

The hills are underlain by a northwest-trending anticline that has been modified by subparallel faults. The oldest rocks, sedimentary strata of middle Miocene age, have been penetrated by wells at a depth of 8,760 feet. They are overlain by upper Miocene, lower and upper Pliocene, and Pleistocene rocks. Only upper Pliocene and Pleistocene strata are exposed at the surface.

The steep north slopes of the Baldwin Hills contrast sharply with their gentle south slopes. Uplift along a fault on the north flank of the hills and erosion by the Los Angeles River in near-Recent time probably account for this asymmetry. North-flowing streams have cut deeper and steeper-walled canyons through the hills than have the south-flowing streams, and much of the drainage follows the surface traces of faults. A southwest-facing scarp of the Inglewood fault (Map 11) extends from the Baldwin Hills to a point beyond the Hollywood Park racetrack, 3 miles to the southeast.

For about half a mile north of Slauson Avenue, roadcuts along La Cienega Boulevard expose gently south-dipping upper Pleistocene marine strata. They are underlain by lower Pleistocene marine strata, which can be seen farther north. These beds rest conformably upon upper Pliocene strata on the southwest side of the Newport-Inglewood fault zone, but are unconformable upon upper Pliocene strata on the northeast side of the fault.

Inglewood Oil Field. The Inglewood oil field (Driver, 1943, pp. 306-309) occupies the central part of the Baldwin Hills along a mile-wide strip that is parallel to the Newport-Inglewood fault zone. The crest of the northwest-trending anticline has been dropped between two faults; the position of the Inglewood fault, which bounds the graben on the northeast, is marked at the surface by a southwest-facing escarpment. Vertical displacement of lower Pleistocene sediments along this fault amounts to about 275 feet, and a strike-slip displacement of as much as 1,500 feet has been estimated on the basis of well-core data. The fault that bounds the graben on the southwest has caused about 160 feet of vertical displacement.

The principal oil accumulations are within five zones in strata that range in age from late Pliocene to middle Miocene. These zones lie at depths of 1,450 feet to more than 5,000 feet below the surface, at the crest of the fold. They include both the highest and lowest stratigraphic horizons known to yield oil in the Los Angeles basin, except for oil that has migrated into schist.

In the Baldwin Hills area, 80 to 200 feet of Pleistocene sand, gravel, clay, and conglomerate is underlain by 1,700 feet of sandstone, shale, and siltstone of the Pico formation (upper Pliocene). They are, in turn, underlain by 3,150 feet of interbedded shale and sandstone of the Repetto formation (lower Pliocene). Only about 1,325 feet of Miocene strata has been encountered. Faunal evidence indicates that the lowest strata penetrated are of late middle Miocene age.

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

GEOLOGIC GUIDE NO. 4

SOUTHWESTERN PART OF THE LOS ANGELES BASIN

1954

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO

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27. Geology of the San Miguelito oil field, Ventura County
28. Geology and occurrences of oil in the Ojai-Santa Paula area, Ventura County
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GEOLOGIC GUIDES

Guide No.

1. Geologic guide for the western Mojave Desert and Death Valley region, southern California
2. Geologic guide through the Ventura basin, southern California
3. Geologic guide for the Los Angeles basin, southern California
4. Geologic guide for the southwestern part of the Los Angeles basin, southern California
5. Geologic guide for the northern part of the Peninsular Range province, southern California

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San Francisco
Bulletin 170
September 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

GEOLOGIC GUIDE NO. 4

SOUTHWESTERN PART OF THE LOS ANGELES BASIN

By ORVILLE L. BANDY *and* KENNETH O. EMERY

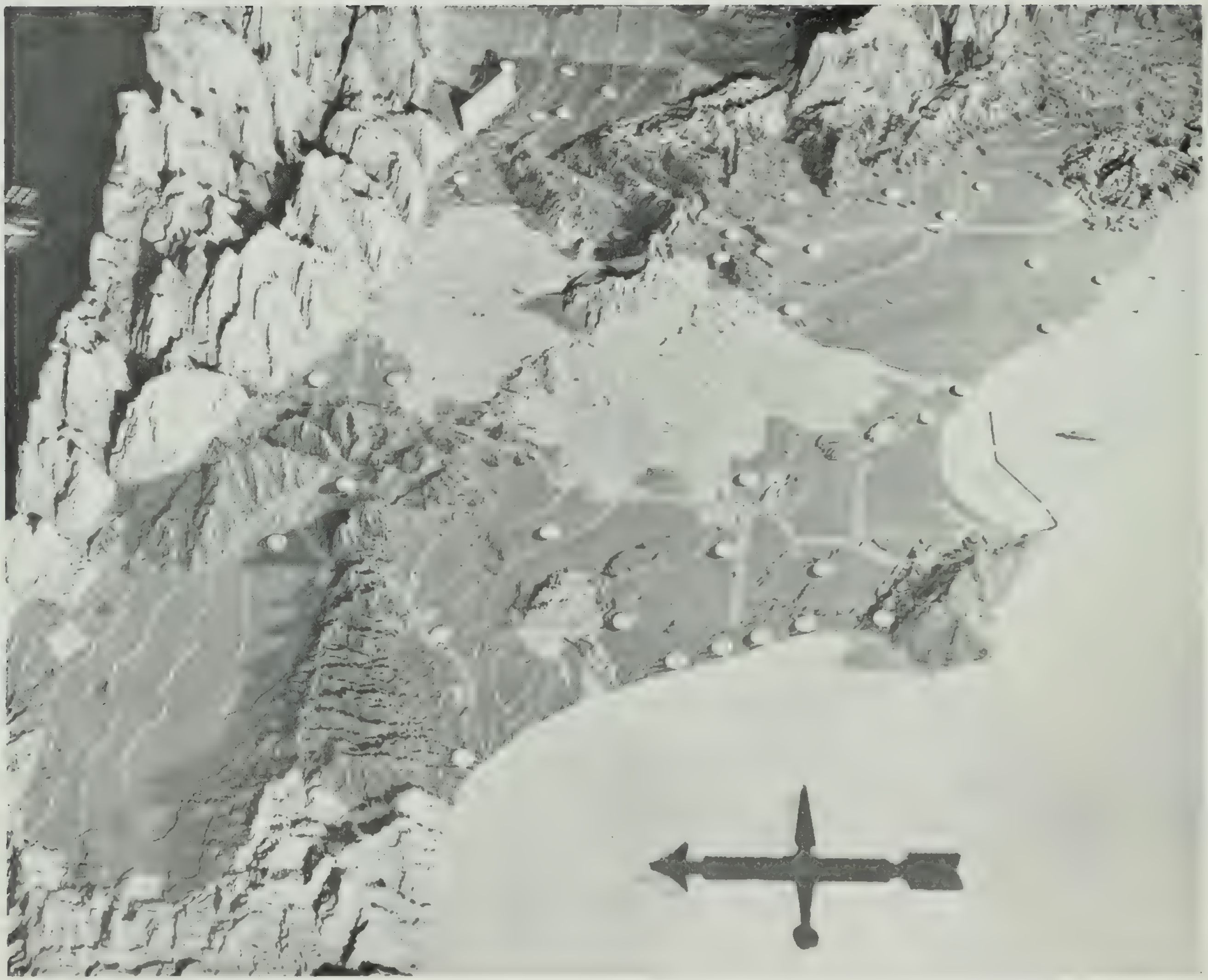

FIGURE 1. Relief map of the Los Angeles basin and adjacent mountains. Palos Verdes Hills in right foreground, Santa Ana Mountains in right background, San Gabriel Mountains in left background, and the Santa Monica Mountains in the left foreground. *Map reproduced through the courtesy of the Museum of Science and Industry of California, Exposition Park, Los Angeles. Photograph by Roy V. George.*

GEOLOGIC GUIDE FOR THE SOUTHWESTERN PART OF THE LOS ANGELES BASIN, SOUTHERN CALIFORNIA

BY ORVILLE L. BANDY * AND KENNETH O. EMERY †

The Palos Verdes Hills, in the southwestern part of Los Angeles County, constitute a small but important uplifted area of the region. Here is exposed a portion of the sedimentary sequence that forms much of the subsurface stratigraphy of the Los Angeles basin, a part of which adjoins the north side of the hills. The basin is further bounded by the Santa Monica Mountains and the Puente Hills on the north and northeast, by the Santa Ana Mountains on the east, and by the San Joaquin Hills on the south. The southwestern and western boundaries are structurally high areas that coincide roughly with the coastal area. Adjoining the south side of the Palos Verdes Hills are two basins that are similar to the Los Angeles basin in size and shape, but are not yet completely filled to sea level by sediments.

Basement rocks of the southwestern part of the Los Angeles basin and the Palos Verdes Hills consist mainly of glaucophane schist and associated metamorphic rocks of probable Jurassic age. Unconformably above this basement terrane are several thousand feet of Miocene and Pliocene strata and a relatively thin surface veneer of Pleistocene terrace sediments. Dune sands of both Pleistocene and Recent age are present in the coastal area, and Pleistocene sands can be observed in the Baldwin Hills and at many other places in the southwestern district.

The Miocene strata (Monterey formation) in the Palos Verdes Hills have been divided into three members as follows: the Altamira shale, 1,000 feet thick; the Valmonte diatomite, 500 feet thick; and the Malaga mudstone, which occurs only in the northern and eastern parts of the hills, about 600 feet thick. The lowest member, the buff to tan Altamira shale, is the most widespread of the three, and is characterized by silty shales in the lower portion, cherty shales in the middle portion, and phosphatic shales in the upper portion. It also contains basaltic sills and tuffaceous beds. The Valmonte diatomite is a diatomaceous shale, buff to white; locally near Walteria and at the top of the hills it is a source of commercial diatomite. The Malaga mudstone is dark gray to buff, and is exposed near the northern and eastern parts of the hills. Rocks of early Pliocene age are represented by about 150 feet of bluish gray glauconitic and foraminiferal siltstones that are disconformable above the Malaga mudstone. These rocks constitute only a thin segment of the Repetto siltstone, which is very thick in the adjacent subsurface section of the Los Angeles basin just north of the San Pedro fault. Exposures of these siltstones occur only along the northern flank of the hills.

Lower Pleistocene marine sediments unconformably overlie the older rocks, and are as much as 600 feet thick in the Palos Verdes Hills. The subdivisions of this lower Pleistocene section are: Lomita marl, Timms Point silt, and the San Pedro sand. Although these units occur in ascending order in some areas, they represent contemporaneous facies elsewhere. Upper Pleistocene marine deposits rest unconformably on the lower Pleistocene sediments in San Pedro, and these, together with some nonmarine deposits, form cappings on the many terraces and constitute the Palos Verdes sand.

Structural features of the Los Angeles basin include the centrally located Newport-Inglewood uplift and other uplifted areas around the margin and near the east boundary of the basin. Faulting and uplift have involved upper Pleistocene sediments, and have influenced the distribution of oil resources of the region. In the Palos Verdes Hills, late Pliocene diastrophism produced considerable folding of earlier strata, including prominent folding west of Point Fermin. Lower Pleistocene marine deposits also were folded and faulted in mid-Pleistocene time, producing an angular discordance of more than 22° between lower and upper Pleistocene deposits. Thirteen marine terraces are recognized between elevations of 100 and 1,300 feet above sea level, and the lowest, or youngest, terrace has been determined by the carbon-14 method to be more than 30,000 years old. Broad valleys with gentle gradients characterize the summit of the hills, and suggest an old erosion surface that may have been formed contemporaneously with the highest terraces.

Natural resources in the southwestern part of the Los Angeles basin include extensive accumulations of oil in Miocene and Pliocene strata, and water in Pleistocene sands. Among the materials obtained commercially in the Palos Verdes Hills are diatomite from the Valmonte diatomite, sand and gravel from the San Pedro sand, flagstone from the cherty and calcareous facies of the Monterey formation, and road metal from the basalts in the Altamira shale. The Lomita marl was once mined for soil dressing and as a source of calcium carbonate for poultry.

Acknowledgments. The writers were assisted in the preparation of this geologic guide by several persons who generously supplied geologic data and helpful suggestions. Of particular usefulness were contributions from U. S. Grant of the University of California, Los Angeles; W. H. Holman of the Standard Oil Company of California; S. G. Wissler of the Union Oil Company; and E. J. Zielbauer of the Los Angeles County Flood Control District.

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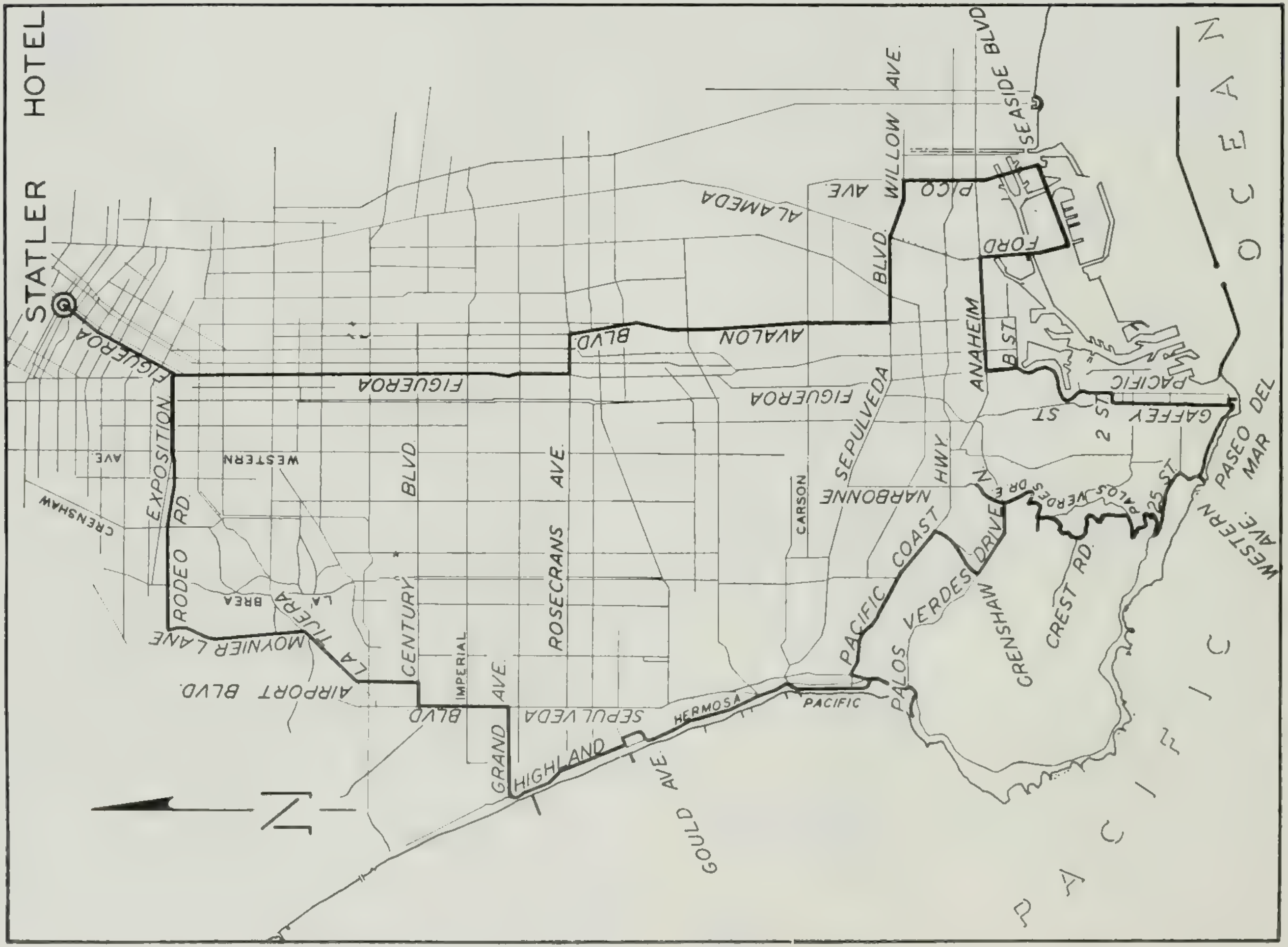

FIGURE 2. Route of field trip through the southwestern part of Los Angeles basin.

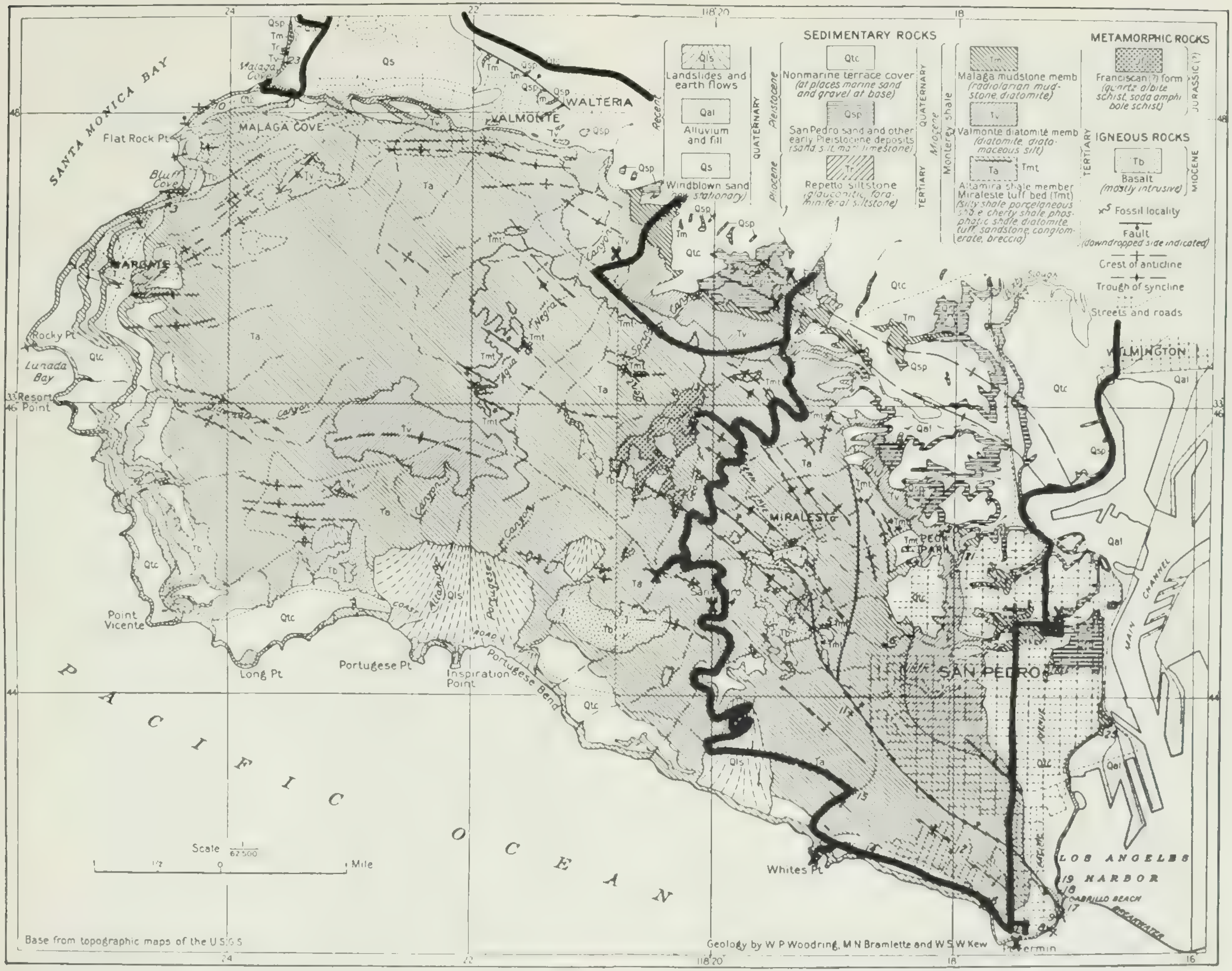
SEDIMENTARY ROCKS
Qls Landslides and earth flows
Qal Alluvium and fill
Qs Windblown sand (now stationary)
Recent
QUATERNARY
Pleistocene
Pliocene
Qtc Nonmarine terrace cover (at places marine sand and gravel at base)
Qsp San Pedro sand and other early Pleistocene deposits (sand, silt, marl, limestone)
Tr Repetto siltstone (glauconitic, foraminiferal siltstone)
QUATERNARY
TERTIARY
Miocene
Monterey shale
Tm Malaga mudstone memb (radiolarian mudstone, diatomite)
Tv Valmonte diatomite memb (diatomite, diatomaceous silt)
Ta Tmt Altamira shale member Miraleste tuff bed (Tmt) (silty shale porcelaneous shale cherty shale phosphatic shale diatomite, tuff, sandstone conglomerate, breccia)
TERTIARY
METAMORPHIC ROCKS
Jf Franciscan(?) form (quartz albite schist, soda amphibole schist)
JURASSIC(?)
IGNEOUS ROCKS
Tb Basalt (mostly intrusive)
MIOCENE
Fossil locality
Fault (downdropped side indicated)
Crest of anticline
Trough of syncline
Streets and roads
SANTA MONICA BAY
Malaga Cove
MALAGA COVE
WALTERIA
VALMONTE
Flat Rock Pt
Bluff Cove
MARGATE
Rocky Pt
Lunada Bay
Resort Point
Point Vicente
Long Pt
Portugese Pt
Inspiration Point
Portugese Bend
COAST ROAD
Whites Pt
MIRALESTE
PECK PARK
SAN PEDRO
WILMINGTON
MAIN CHANNEL
LOS ANGELES HARBOR
CABRILLO BEACH
BREAKWATER
Fermin
PACIFIC OCEAN
Scale 1/62 500
1 1/2 0 1 Mile
24
22
118°20
18
16
33°46
48
44
Base from topographic maps of the U.S.G.S.
Geology by W. P. Woodring, M. N. Bramlette and W. S. W. Kew

FIGURE 3. Geologic map of the Palos Verdes Hills, showing route of field trip. *Map published by permission of the American Association of Petroleum Geologists.*

ITINERARY

Miles

0.0 Start from Statler Hotel at Figueroa Street and Wilshire Boulevard, and go south on Figueroa Street. On Flower Street (one block east), between Fourth and Fifth Streets, are good exposures of Pliocene siltstones which dip 35°S. and are covered by Pleistocene alluvium and Recent asphalt.

2.8 Turn right (west) on Exposition Boulevard past the University of Southern California.

4.3 Cross Western Avenue.

4.6 Jog left to Rodeo Road and continue west.

5.9 Cross Crenshaw Boulevard.

7.1 Cross La Brea Boulevard. This area is Ballona Gap, a notch that was cut through the Newport-Inglewood uplift by the Los Angeles River during post-Pleistocene time. The channel is now occupied by a small creek and by peat deposits atop which some of the new housing units have been built.

8.0 Turn left (south) on Moynier Lane and proceed up the north slope of the Baldwin Hills. Moynier Lane becomes La Cienega Boulevard in the southern part of the Baldwin Hills. An east-west fault bounds the north side of the hills here, and to the south nearly horizontal Pleistocene sand and gravel beds are exposed in the roadcuts.

9.3 Stop at the Inglewood oil field. This field, in the Baldwin Hills, is on the Newport-Inglewood uplift, one of the major oil-producing trends in the Los Angeles basin. The main producing area lies within a northwest-trending faulted anticline, the crest of which is a graben. The Inglewood fault, which bounds the graben on the east, lies about half a mile east of the road. Production is obtained from lower and upper Pliocene and upper Miocene sediments, and is restricted to five main zones. The upper and most prolific zone, the Vickers-Machado zone, is encountered about 1,425 feet below the surface west of the Inglewood fault and about 1,200 feet below the surface east of the fault. It embraces the lower 770 feet of the upper Pliocene section and the upper 510 feet of the lower Pliocene section. A second zone, the Rindge zone, is immediately beneath the first and attains a maximum thickness of 1,000 feet. Production usually is confined to the upper few hundred feet because of the presence of bottom water. The next zone, the Rubel zone, lies directly beneath a 60-foot shale bed at the base of the Rindge zone, and it attains a maximum thickness of about 800 feet. Production from this zone also is usually restricted to the upper few hundred feet because of bottom water.

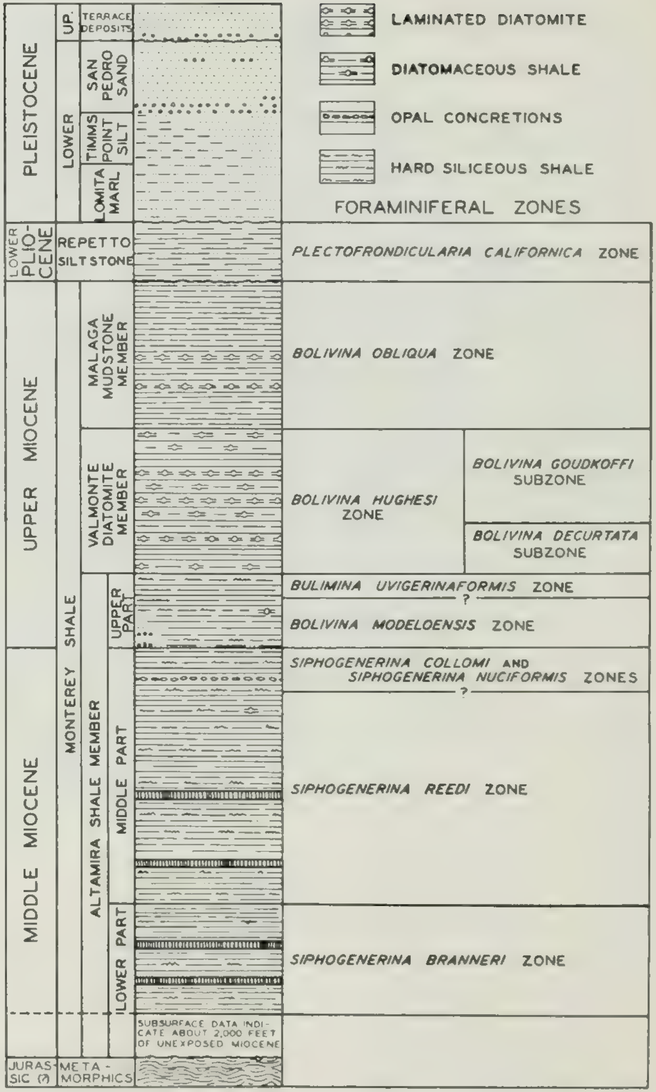

FIGURE 4. Generalized stratigraphic section and related foraminiferal zones of the Palos Verdes Hills. *Adapted from Woodring, Bramlette, and Kew, U. S. Geol. Survey Prof. Paper 207.*

In late years substantial production has been developed from a limited area beneath the Rubel zone, from sands known as the Moynier zone, within the lower Pliocene and upper Miocene (upper Delmontian) section. A still deeper producing zone, the Sentous, is encountered at depths of more than 6,000 feet, within the upper few hundred feet of a section of middle Miocene sandstones and volcanics which exceeeds 3,000 feet in thickness. This zone embraces the lower Mohnian and Relizian (?), and is important commercially only in the northwestern part of the field. It is among the oldest, in a stratigraphic sense, within the Los Angeles basin. The highest oil zone (Vickers) is stratigraphically the youngest of the producing zones in the oil fields of the basin. Total production from the Inglewood field has been about 190,000,000 barrels of oil ranging from 13° to 38° gravity A.P.I. The average monthly production for 1953 was about 400,000 barrels.

11.3 Turn right (southwest) on La Tijera Boulevard.

12.6 Turn left (south) on Airport Boulevard.

14.0 Turn right (west) on Century Boulevard at north side of the Los Angeles International Airport.

14.6 Turn left (south) on Sepulveda Boulevard (U. S. 101A) and drive under airplanes.

15.6 Cross Imperial Boulevard.

16.4 Turn right (west) on Grand Avenue. For about a mile pass through an area of Pleistocene sand dunes that is characterized by rolling topography and brown soil.

17.1 El Segundo oil field, with Standard Oil Company refinery, is on left. Recent dunes lie about a mile farther west.

The westernmost oil-producing structure in the Los Angeles basin occurs along the coast in the vicinity of El Segundo and Playa del Rey. A buried ridge of schist controlled the structure that governed oil accumulation. Producing zones are lower Mohnian Miocene basal sediments which overlap the schist, and a fractured zone in the upper part of the schist. Some faulting occurs here, but it does not cut the metamorphic rocks and evidently has had no bearing on the oil accumulalation. Depth of production is about 6,850 feet at the crest of the structure and about 7,750 feet on the southern edge of the field. Production through 1953 totaled more than 12,500,000 barrels of 15° to 28° gravity oil. Present monthly production is about 6,700 barrels.

To the north of El Segundo is the areally larger Playa del Rey oil field that extends from Playa del Rey northward across the tidal marshes of Ballona Creek into the southern part of the city of Venice. Production is obtained from a basal conglomerate and fractured schist and from superposed folded sediments whose anticlinal structure is largely the result of deposition and compaction over an eroded ridge of the basement rocks. A long erosion interval, prior to deposition of Miocene sediments, is indicated by the dissected topography of the buried schist ridge. Gradual submergence occurred in late Miocene time, with accompanying deposition of an apron of schist-bearing clastic sediments around the ridge and in depressions produced by the drainage. Next was deposited a conformable series of dark brown phosphatic muds that are now compact nodular shales. The schist-bearing clastic strata and associated beds of sandstone range from less than a foot to 234 feet in thickness, and the overlying shales range from 60 to 308 feet in thickness. About 4,500 feet of sediments, mostly shale and sandy shale of Miocene and Pliocene age, lie above the nodular shales. Production of oil is from lower Pliocene sands, and principally from the basal conglomerate and fractured basement rocks that represent embayments formed in the erosion cycle preceding the Miocene submergence. Schist-bearing clastics and associated sandstones of the southwestern plunge are now used for stand-by gas storage for both commercial and residential consumption. Production through 1953 totaled about 57,000,000 barrels of 19° to 24° gravity oil. Present monthly production averages about 43,000 barrels.

17.6 Drive through town of El Segundo.

18.0 Pass through Recent sand dunes, part of a 10-mile-long transverse dune complex that extends from Playa del Rey to Redondo Beach.

18.2 Curve to left (south) on Highland Avenue. Note the groin across the beach; the accumulation of sand on the north side of this groin indicates a prevailing southward longshore current. The beach has been widened by sluicing sand obtained from dunes about 3 miles farther north.

18.7 Drive through Standard Oil Company tank farm.

19.6 Houses are built on dunes that are held in place partly by *Mesembryanthemum*, a succulent ground cover.

20.9 Turn left (east) on Manhattan Beach Boulevard.

21.0 Turn right (south) on Morningside Drive.

21.1 Turn left (east) on Tenth Place.

21.2 Turn right (south) on Valley Drive.

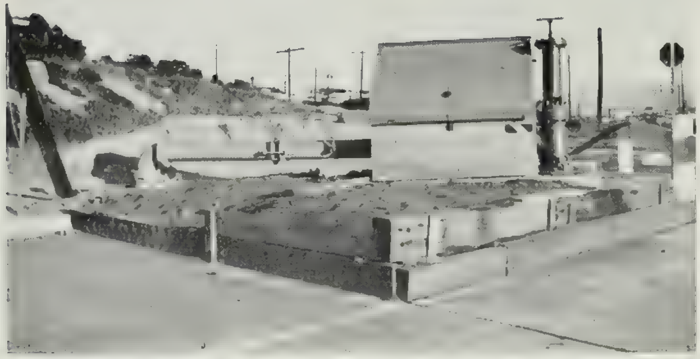

FIGURE 5. One of the water injection wells at Manhattan Beach.

Miles

21.4 Stop in area of West Coast Basin Barrier Project.

Progressive sea-water intrusion along an 11-mile coastal reach of the West Coast ground-water basin, from Playa del Rey to Redondo Beach, has become critical because of a heavy pumping basin overdraft in excess of 50,000 acre-feet annually. The field experimental barrier project, established and operated by the Los Angeles County Flood Control District under contract with the California State Water Resources Board, was initiated to determine the feasibility of checking the inland encroachment of sea water in an area of receding pressure levels, through the creation of a fresh-water pressure ridge, approximately 1 mile in length, adjacent and parallel to the Pacific shore line at Manhattan Beach and Hermosa Beach.

The fresh-water barrier was created by an injection of chlorinated imported water into the affected Silverado water-bearing zone (upper and lower Pleistocene) through wells spaced at 500-foot intervals some 2,000 feet inland and parallel to the coast line. The Merged Silverado aquifer was found to be capped at or near sea level by a stratum of relatively impervious silts and sandy clays. Localized stripping of this cap by longshore currents and transverse channeling, accentuated by the local pattern of well pumping, probably accelerated inland saline encroachment in the coastal reach subject to investigation. The character of the coastal sediments was such as to require that the injection wells be properly sealed throughout the zone of relatively impervious sediments capping the Merged Silverado zone. Maximum well acceptance rates were obtained at gravel-packed injection wells.

From the initial down-coast pressure gradient of from 5 to 10 feet below mean sea level, a continuous pressure ridge was created and sustained at an average of 3.5 feet above sea level at inflows averaging approximately 0.5 c.f.s. per well. The quantity of injected water required for maintenance of the ridge was found to be less than anticipated. The fresh-water ridge serves the dual purpose of preventing sea-water intrusion and of replenishing the West Coast ground-water basin. Pressure profile gradients definitely show that any loss of fresh water seaward is negligible.

Continue on Valley Drive.

21.9 Turn right (west) on Gould Avenue (becomes 27th Street).

22.2 Turn left (south) on Hermosa Avenue. The beach on right beyond the houses is a part of Hermosa Beach.

23.0 Downtown Hermosa Beach.

23.8 Edison Power Company.

24.3 Stop in area of wave damage.

In this area a breakwater built about 1939 for a boat harbor has served to stop the southward movement of sand along the beach, by damming it on the north side. Sand south of the breakwater was partly carried northward into the quiet water behind the breakwater by wave refraction, and partly moved southward to the head of Redondo submarine canyon, which lies at the pier a quarter of a mile to the south. Loss of sand south of the breakwater, coupled with lack of normal replacement from the north, caused the beach to become narrower and narrower, and finally to disappear entirely. Subsequently, waves whose energy formerly was dissipated in crossing the beach, struck the shore with great force, cutting it back and removing a board walk and about 15 houses. In an effort to remedy the situation, a seawall was constructed of quartz diorite blocks quarried from localities in Riverside County. Recently almost every year has seen partial destruction of the seawall, followed by expensive repairs; final cure of the situation will require either completion of the breakwater or removal of the part that has been built.

24.5 Angle up the hill on Pacific Avenue in downtown Redondo Beach.

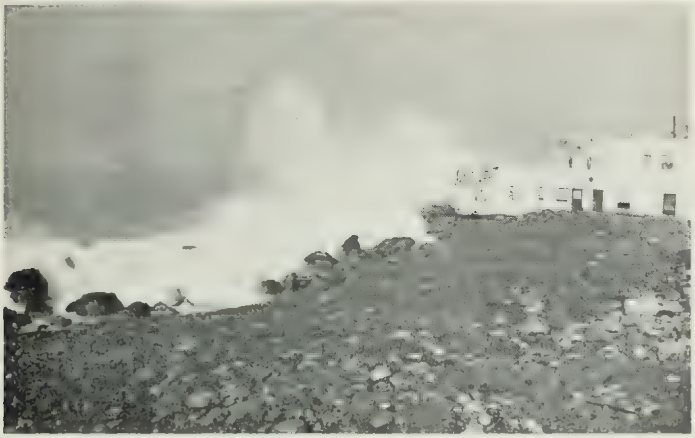

FIGURE 6. Destructive waves at Redondo Beach on January 17, 1953.

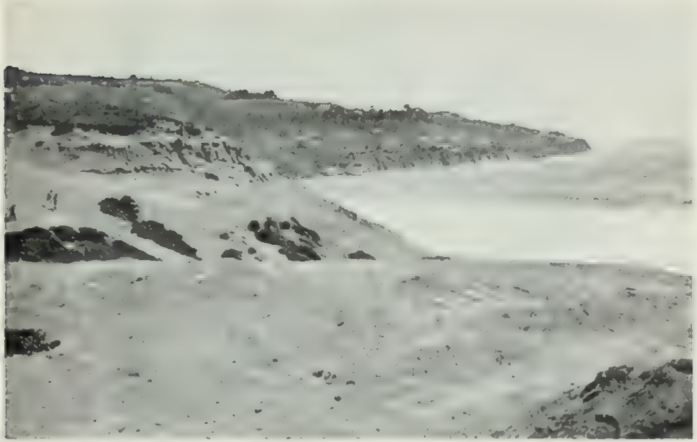

FIGURE 7. Malaga Cove. Pleistocene dune sand in foreground, terraced headland in distance.

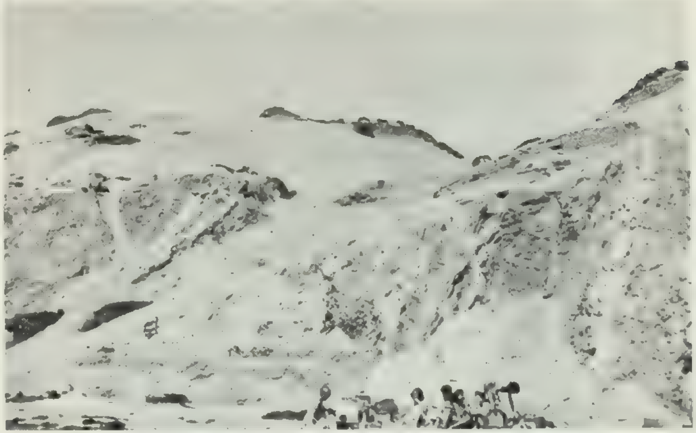

FIGURE 8. Fault in Malaga mudstone, which is in part concealed by Pleistocene dune sand.

Miles

24.9 Turn right (southwest) on Esplanade. Note three or four well-developed terraces on the west slope of the Palos Verdes Hills.

26.5 Jog around the left side of club building on Paseo de la Playa.

26.9 Park in lot and proceed on foot along the beach at Malaga Cove.

The path to the beach passes through Pleistocene dune sand atop a terrace that has been tilted to the north. The beach in this area is well known for its deposit of black sand, which consists largely of ilmenite, magnetite, and epidote. The heavy minerals form layers that alternate with light-colored layers of quartz and feldspar to form a well-laminated deposit. Common on the surface are other beach features such as swash marks, rill marks, linguloid ripples, sand domes, and sand holes. Scattered about the beach are pieces of kelp, commonly with pebbles in their holdfasts that have been rafted from positions half a mile or more offshore. Here and there are also many pebbles and cobbles riddled by pelecypod and worm borings.

Nonmarine Pleistocene to Recent terrace deposits unconformably overlie highly deformed strata in the sea cliff. Proceeding along the beach to the south, one encounters San Pedro (?) sand, faulted and nearly vertical beds of the Malaga

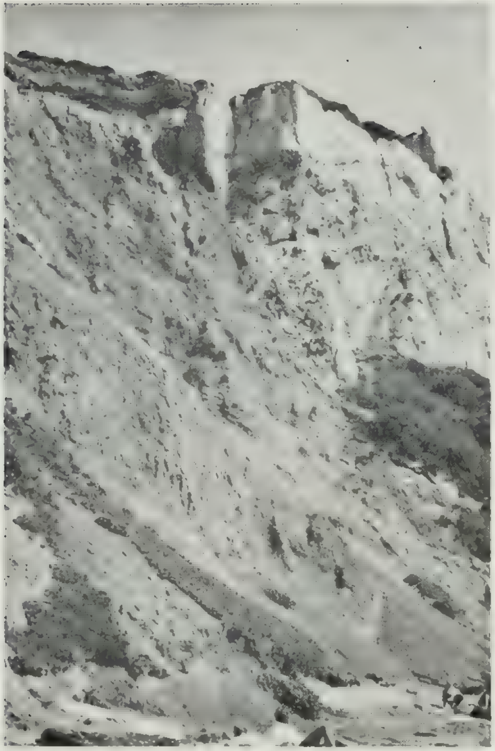

FIGURE 9. Fault contact between Valmonte diatomite on the right and Malaga mudstone on the left. Note the steep dip of the mudstone and the drag folding in the diatomite.

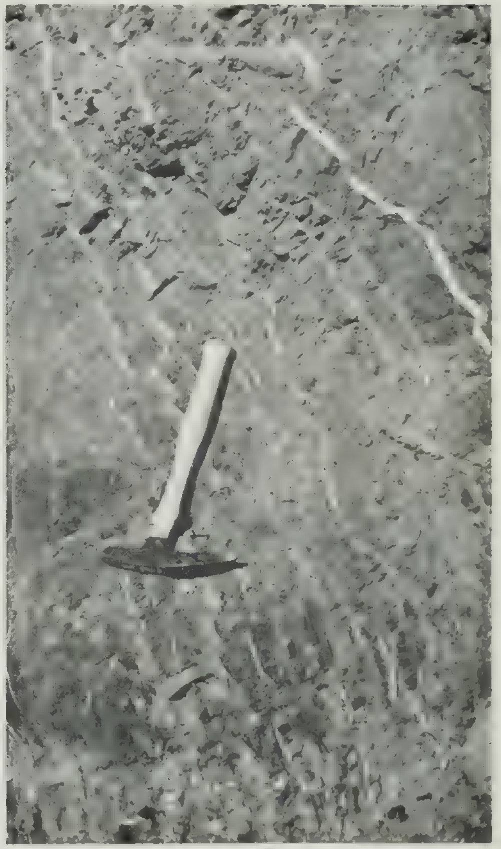

FIGURE 10. Minor faults and imbricate bedding in the Valmonte diatomite.

mudstone member of the Monterey shale, a prominent syncline with Repetto siltstone in its core, and additional faulted and folded beds of the Valmonte diatomite member and the Malaga mudstone. Enormous radiolarians occur in the Malaga mudstone, and can be seen with the unaided eye. On the basis of foraminiferal evidence elsewhere in this member, it is thought to have been deposited in water several thousands of feet deep. Highly diversified foraminiferal faunas occur in both the Valmonte diatomite and the Repetto siltstone. Diatom beds, chert, and phosphatic layers characterize the Valmonte diatomite

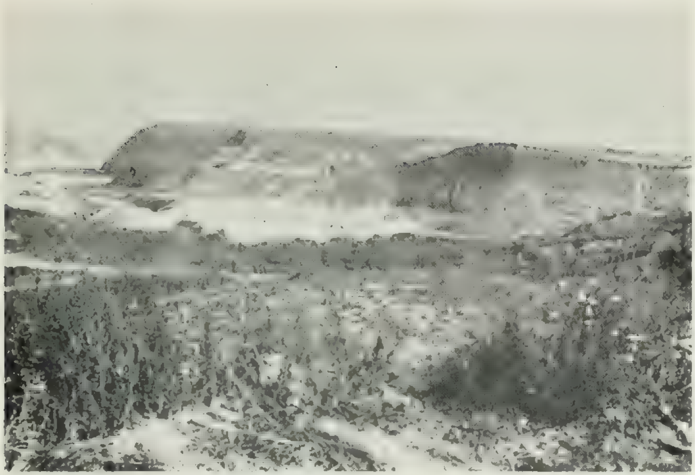

FIGURE 11. Dicalite quarry in the Valmonte diatomite near Walteria.

Miles

at this locality. When wet, the diatomaceous shale appears black and the phosphatic layers appear light gray or brown.

Near the middle of the cove is a large landslide that consists of shale with many small slickensided surfaces. Groundwater moving atop the slip plane escapes from the toe of the slide in several small springs.

28.8. Pavilion near south end of Malaga Cove on Paseo del Mar. Go south on Via Arroya from Pavilion. Note terraces crossed by road.

29.0 Turn left (east) on Via Almar.

29.4 Turn left (east) on Palos Verdes Drive.

29.6 Turn left (north) on Palos Verdes Boulevard.

30.8 Turn right (northeast) on Elena Avenue.

31.0 Turn right (northeast) on Vista del Mar.

31.1 Turn right (east) on Pacific Coast Highway (U. S. 101A).

31.8 Pass through section of Pleistocene sand dunes in roadcut.

Dunes are being eroded by bulldozers and overlain by houses.

33.3 Cross Hawthorne Boulevard. The Torrance oil field, spotted with old wooden derricks, is located to the northeast.

34.5 Turn right (south) on Rolling Hills Road.

34.9 Angle right (southwest) on Crenshaw Boulevard.

Miles

35.5 Stop at diatomite quarry. About a million tons of diatomite has been removed during the past 20 years. Main uses, based on the high porosity of the material, have been for insulation and filtering aids. A pound of it has a surface area equivalent to about eight football fields. The tall, straggly plants growing sparsely atop the waste piles are wild tobacco.

35.9 Turn left (east) on Palos Verdes Drive North. Pass through Valmonte diatomite and Altamira shale.

37.6 Turn left (north) on Narbonne Avenue. Pass up section through Altamira shale, Repetto siltstone, and San Pedro sand.

38.5 Stop at Chandler quarry in San Pedro sand. Crossbedding is very well shown in the side of the quarry. Mammal bones are occasionally found in the sand.

38.9 Rich foraminiferal collections can be made from the Repetto siltstone here.

39.2 Return to south, crossing Palos Verdes Drive North and passing reservoir on left. This contains Colorado River water and is one of the westernmost outcrops of this water.

39.5 View of Union Oil Company refinery and tank farm on east. Cities are San Pedro, Wilmington, and Long Beach in the distance. From northwest to east, the ranges in the far distance are the Santa Monica, San Gabriel, San Bernardino, and Santa Ana Mountains.

40.9 Turn right (west) on dirt road along side of hill.

41.3 Stop at exposure of schist, chert, and quartzite, presumably of Jurassic age. The schist is characterized by the mineral glaucophane, which gives it a blue-green color. This is the southernmost outcrop of this type of schist on the mainland in California, but similar rock occurs on Catalina Island, about 25 miles southward, and also has been encountered in wells on the west side of the Los Angeles basin.

41.7 Turn right (south) on Palos Verdes Drive East.

42.1 Turn right (west) past gate on Eastfield Drive, and continue up hill. Note terraces on north slope.

43.8 Turn left (east) on Crest Road.

44.6 Stop at terrace deposit. This is the twelfth terrace above sea level and has been cut on Altamira shale. Note abundance of gravel, shells, and pholad borings.

45.0 Note terraces on south slope of hills.

45.5 Turn right (southwest) on Palos Verdes Drive East at Marymount School.

47.5 Turn left (east) on 25th Street.

48.4 Pass ancient landslide area on south.

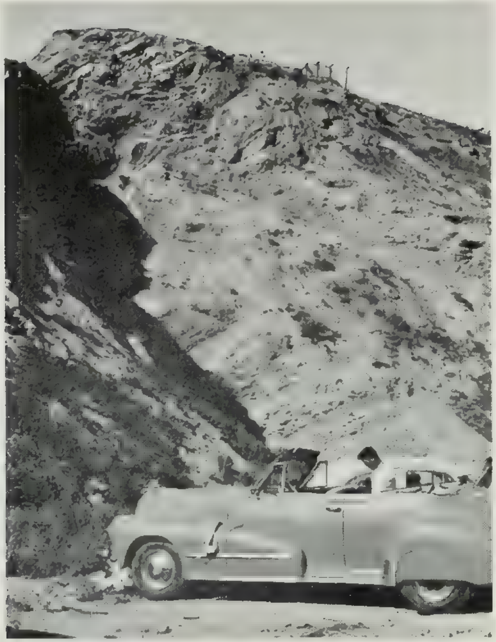

FIGURE 12. Recumbent folds in Altamira shale at Whites Point. Small oil seeps occur in this area.

Miles

49.0 Turn right (south) on Western Avenue. This is the south end of one of the country's longest city streets, 27 miles with no turns except near this end.

49.8 Turn left on Paseo del Mar, and thence right on the road to Whites Cove.

50.0 Stop at exposure of recumbent folding in Altamira shale. A well-developed terrace is now being cut across tilted beds in shallow water. Oil seeps exist in this area.

50.3 Turn right (east) on Paseo del Mar.

51.9 Note roadcut below guns of Fort McArthur. Pebbles of glaucophane schist occur in this part of the Altamira shale. Large cobbles and boulders of schist up to 4 feet long occur in the side of the seacliff below the road.

52.1 Turn left (north) on Gaffey Street.

52.1 Turn right (east) on Shepard Street.

Miles

52.2 Turn left (north) on Carolina Street and park.

Walk south to the Point Fermin landslide. This slide began in 1929 and moved for a period of several months. Movement was recurrent in 1940 and again in 1941 during and after extended periods of heavy rain. Altamira shales dip seaward toward the steep sea cliff.

52.3 Turn left (west) on 40th Street.

52.4 Turn right (north) on Gaffey Street.

54.9 Turn right (east) on Second Street in San Pedro.

55.2 Stop at road cut just east of Pacific Avenue, which exposes Lomita marl, Timms Point silt, and San Pedro sand. One of the most famous Pleistocene fossiliferous marls of the world, the Lomita marl, occurs here. Specimens include abundant Foraminifera and bryozoans. Above the Lomita marl is the Timms Point silt, which is sparsely fossiliferous at this locality. The San Pedro sand has been removed east of this stop. Unconformably above the lower Pleistocene formations is the upper Pleistocene Palos Verdes formation, which contains marine fossils at the base and grades upward into chocolate-colored nonmarine beds. The lower Pleistocene beds dip about 23° SE and form a flank of the Gaffey syncline. Note how the gaper clam (*Schizothaerus nuttallii*) in the Palos Verdes formation has burrowed into the underlying Timms Point silt.

53.3 Turn right (south) on Mesa Street.

55.4 Turn right (west) on Fourth Street.

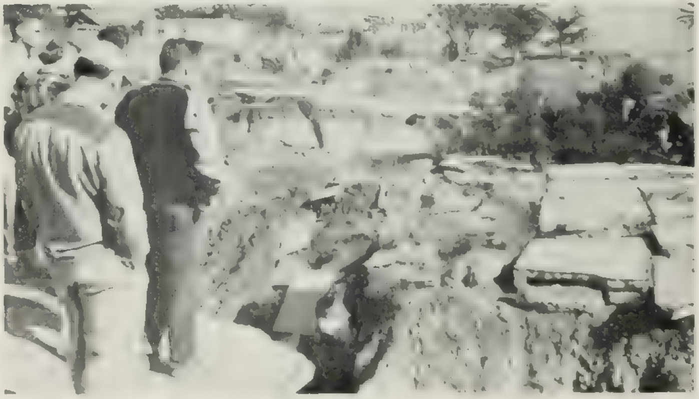

FIGURE 13. Point Fermin landslide. Slabs are a part of the pavement of Paseo del Mar.

Miles

55.5 Turn right (north) on Pacific Avenue.

56.3 Angle to left on Pacific Avenue, which changes to B Street. Pass through wind gap whose uplift has resulted in ponding of a stream to form Bixby Slough north of hill.

57.0 Pass both ancient and modern kitchen middens in road cut.

57.4 The San Pedro sand is exposed here.

58.4 Turn left (north) on Figueroa Street (State Highway 11). Union Oil Company plant is on left.

59.0 Turn right (east) on Anaheim Street.

60.2 Pass through Wilmington oil field.

60.3 Turn right (south) on Henry Ford Boulevard.

62.2 Turn right (west) on Anchorage Road.

62.3 Wilmington oil field.

Between Wilmington and the Los Angeles County Flood Control Channel in Long Beach is the Wilmington oil field. Commercial production began here in 1936 after a thorough seismic survey was made of the area. The main structure is an anticlinal nose that plunges to the northwest. Four main north-trending faults transect the anticlinal structure and divide the field into five structural blocks. From west to east these breaks are designated the Wilmington fault, Ford fault, Power Line fault, and the Long Beach fault. These are normal faults, and all but the Power Line fault hade to the east. Displacements are mostly less than 350 feet. There is considerable thickening of intervals of the Repetto formation on the downthrown blocks, accompanied by progressive increase in vertical displacement on the faults with depth down to the top of the Miocene section. Below this horizon displacement is relatively constant. Productive horizons, which are sealed off in the individual fault blocks, comprise the Tar zone, Ranger zone, Terminal zone, and Ford zone. The first is in the Repetto siltstone, the second spans the Pliocene-Miocene contact, and the others are in the upper Miocene beds. Production through 1953 was in excess of 650,000,000 barrels of 13° to 32° gravity oil, A. P. I. The present production rate is about 3,625,000 barrels per month. To the north and west is the Torrance oil field, an extension of the Wilmington field. Production there is largely from a part of the Terminal zone of the Wilmington field.

For more than 3 decades a slight surface subsidence of a wide area in the southern Los Angeles coastal plain, apparently a result of the decrease of pressure in confined water bodies (aquifers), has been detected by repeated spirit leveling. A greatly accentuated surface subsidence has occurred more recently over the producing area of the Wilmington oil field, the maximum decrease in elevation of about 20 feet occurring near the center of the depressed area close to the Edison steam electric generating plant on eastern Terminal Island. This larger subsidence has been attributed to large decreases in reservoir pressures in the oil-producing zones. Expensive remedial work, such as erection of dikes, filling of depressed land, and raising of wharves, has been required. The bending of the prism of sediments overlying the contracting oil zones has produced shearing stresses in the strata which have damaged a large number of oil wells.

62.4 Turn right (south) on Henry Ford Boulevard.

63.0 Turn left (east) on Seaside Boulevard. The pumping wells on both sides of the route produce from beneath the harbor area to the south.

63.8 Edison power plant.

65.0 Turn left (north) on Pico Avenue.

65.4 Closely spaced pumping wells along the flood-control channel here are whipstocked under the business district of Long Beach to the east.

68.0 Turn right onto ramp leading up to Willow Avenue and proceed west. Signal Hill is located to the east.

69.7 Cross Alameda and proceed west on East Sepulveda Boulevard past Richfield Oil Corporation laboratories and refinery.

71.4 Turn right (north) on Avalon Boulevard.

73.1 Cross East Carson Street.

75.3 Dominguez oil field is on the right.

The Dominguez field, discovered in September, 1923, currently has 339 producing wells and a total cumulative production of 200,000,000 barrels as of January 1, 1954. Production is from eight zones, comprising the basal 2,150 feet of the lower Pliocene section and the upper 1,800 feet of the underlying Miocene section. The first zone, which lies at a depth of approximately 3,350 feet near the apex of the structure, is now being subjected to water flooding. A deep well penetrated approximately 200 feet of upper Pleistocene strata, 530 feet of lower Pleistocene, 2,230 feet of upper Pliocene, 2,800 feet of lower Pliocene, 5,650 feet of Miocene, and entered the schist basement at 11,366 feet. About 700 feet of interbedded pyroclastics and shale was encountered in the lower part of the Miocene section. The field is located on a faulted anticline that is cut by a series of northwest-trending transverse normal faults and a complicated system of lateral thrusts.

Miles

77.0 Angle left on San Pedro Street.

78.2 Turn left (west) on Rosecrans Avenue; Rosecrans oil field.

The Athens-Rosecrans oil field, discovered in 1924, has a total cumulative production of 72,000,000 barrels as of January 1, 1954. Like Dominguez, the Athens-Rosecrans structure is a complicated faulted anticline along the Newport-Inglewood fault trend. There are several producing areas with oil accumulation controlled by cross faulting. The stratigraphy is similar to Dominguez, and the production comes from the lower Pliocene and upper Miocene strata. None of the wells in this area have gone deep enough to encounter basement rocks.

79.0 Turn right (north) on Figueroa Street.

80.0 Athens oil field.

87.4 Pass the University of Southern California.

90.3 End at Statler Hotel.

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STATE OF CALIFORNIA
DEPARTMENT OF NATURAL RESOURCES

GEOLOGY OF SOUTHERN CALIFORNIA

BULLETIN 170

GEOLOGIC GUIDE NO. 5

NORTHERN PART OF THE PENINSULAR RANGE PROVINCE

1954

DIVISION OF MINES
FERRY BUILDING, SAN FRANCISCO

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San Francisco
Bulletin 170
December 1954

GEOLOGY OF SOUTHERN CALIFORNIA

Edited by RICHARD H. JAHNS

GEOLOGIC GUIDE NO. 5

NORTHERN PART OF THE PENINSULAR RANGE PROVINCE

By RICHARD H. JAHNS

GEOLOGIC GUIDE FOR THE NORTHERN PART OF THE PENINSULAR RANGE PROVINCE, SOUTHERN CALIFORNIA*

By Richard H. Jahns †

INTRODUCTION

Route of Travel. This geologic guide deals with parts of Los Angeles, San Bernardino, Riverside, and San Diego Counties, in southern California, and in effect is a sampling of the geology and mineral deposits in the northern part of the Peninsular Range province. The main route of travel, essentially an elongate loop (fig. 1), begins in downtown Los Angeles, extends eastward to Pomona, and from there extends southeastward to Lake Henshaw via Corona and the Elsinore-Temecula Valley. The return part of the loop trends in a general northerly direction to the San Jacinto Mountains and San Gorgonio Pass, and thence westward to Los Angeles. The entire route is approximately 320 miles long, involves travel over good roads, and can be traversed without undue haste in 2 days.

Several points of special interest can be reached by means of short side trips, about 87 miles in aggregate length, that are included in the guide. An additional trip, 82 miles long, has the form of an auxiliary loop through the Escondido-Ramona area, in San Diego County.

Both the main tour and the side trips provide excellent opportunities for observation and study of fault phenomena, geomorphic features, and a wide variety of rock types and mineral deposits. Encountered along the main route of travel are the Elsinore and San Jacinto fault zones, the Pala and Rincon pegmatite districts, and the contact metamorphic deposits at Crestmore.

Form of the Guide. This guide includes a general outline of Peninsular Range geology, annotated road logs for all routes of travel, and numerous maps, sections, and photographs that illustrate the principal geologic features. General descriptions of several areas, mining districts, and geologic units are included within the road logs. A continuous series of seven strip maps shows the geology along approximately half of the route, and three other maps provide similar coverage for selected areas along the remainder of the route.

Cumulative mileages from the starting point at the Los Angeles Civic Center are indicated for the main tour as followed in a counter-clockwise direction around the loop; the figures appear along the margins of the road log and on the maps. Mileages for the side trips and alternate loops are taken from the respective junctions with the main route of travel.

Acknowledgments. The data used in preparing this guide have been obtained from many sources, which are specifically indicated on the illustrations and in the text. In addition, special thanks are due Richard Merriam of the University of Southern California, who supplied all of the information that appears on Map 9; Clarence R. Allen and C. Wayne Burnham of the California Institute of Technology, who contributed unpublished data on the San Gorgonio Pass and Crestmore areas, respectively; and Bennie W. Troxel of the State Division of Mines, who compiled parts of the strip maps. The writer was assisted in a final field check of the route by Troxel and Lauren A. Wright.

GEOLOGY OF THE NORTHERN PENINSULAR RANGE REGION

General Features

The Peninsular Range province is a well-defined geologic and physiographic unit that extends southeastward from the latitude of Los Angeles to the southern tip of the Baja California peninsula, a distance of approximately 900 miles. It is bounded on the northeast by the Colorado Desert (Coachella and Imperial Valleys) and the Gulf of California, and it extends southwestward beneath the Pacific Ocean to form the continental borderland, parts of which appear as Santa Catalina, San Clemente, and other islands. Only the northernmost part of this extensive province is dealt with in the present geologic guide; this part includes the Los Angeles Basin and adjoining hills, the Santa Ana Mountains, the Elsinore-Temecula Valley, the Agua Tibia Mountains, the Warner Basin and adjoining ranges, the Perris and Anza Uplands, the San Jacinto Mountains, and San Gorgonio Pass (fig. 1).

The altitude and relief of this region decrease in a general way from east to west, and its coastal portion is marked by an irregular fringe of lowland country. Beneath this coastal plain and the more extensive lowland area of the Los Angeles Basin is a complex section of sedimentary rocks that range in age from Upper Cretaceous to Recent. Some volcanic rocks of Tertiary age also are present. The inland areas, in contrast, are underlain chiefly by igneous and metamorphic rocks of Mesozoic age and by some metamorphic rocks of probable Paleozoic age. Younger sedimentary rocks, chiefly nonmarine, are preserved in a few basins and valleys, and remnants of volcanic rocks appear locally. Numerous faults have been recognized, and some of them have lengths measured in tens of miles and known displacements amounting to many thousands of feet.

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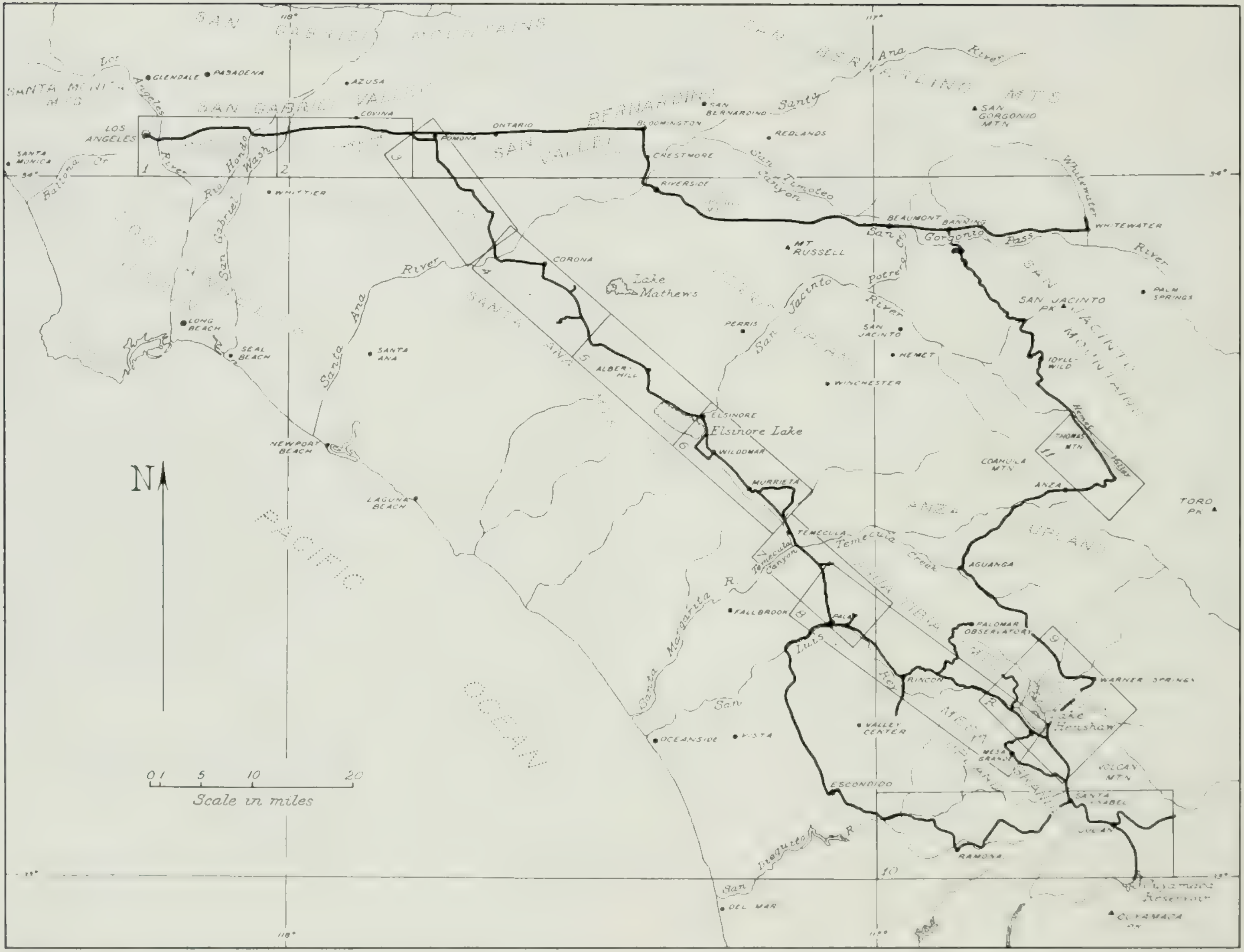


FIGURE 1. Index map of a part of southern California, showing major geographic features, routes of travel described in the road logs, and the areas for which geologic map coverage is provided.

The geology of large parts of the region has been described by Dudley (1935), Ellis and Lee (1919), Engel (1933), Fairbanks (1893), Fraser (1931), Jahns (1954), Larsen (1948), Mann (1951), Merriam (1946), Merrill (1914), Reed (1933), Sauer (1929), Waring (1919), and Woodford, et al. (1954), and specific areas and problems have been discussed by these and numerous other investigators. For more complete and detailed treatment of Peninsular Range geology than appears in this guide, the reader should consult the papers and reports that are listed at the end of the road-log descriptions.

The Geologic Section

The rocks in the northern part of the Peninsular Range province can be grouped into two fundamental age divisions on the basis of differences in lithology, structure, and degree of metamorphism. These divisions are everywhere separated by a profound unconformity, which reflects a major episode of diastrophism, igneous invasion, and metamorphism that occupied a significant part of Cretaceous time.

Older Rocks. The oldest exposed rocks in the region are schists, gneisses, quartzite, and marble that in general represent original clastic sediments and subordinate interlayered volcanic rocks. They form sections as much as 22,000 feet thick in parts of the eastern mountain ranges, but in most areas they appear as smaller masses that are surrounded or flanked by younger igneous rocks. A Paleozoic age for this ancient terrane is suggested by two possible fossil occurrences (Webb, 1939; Miller, 1944, pp. 21-25), and the rocks may correspond in part to fossiliferous Paleozoic strata that are preserved in the San Bernardino Mountains to the north.

Farther west, in the Santa Ana Mountains and adjacent areas, is a great thickness of mildly metamorphosed slaty rocks, schists, quartzite, conglomerate, and limestone that are at least in part of Triassic age. Known collectively as the Bedford Canyon formation (Larsen, 1948, pp. 18-22), these rocks appear to grade into metasedimentary and metavolcanic rocks that have been termed Julian schist (Merrill, 1914, pp. 638-642; Hudson, 1922, pp. 182-190) in areas to the southeast. The relations between these two formations and the presumably older metamorphic rocks to the east and northeast are not fully understood at the present time.

Resting unconformably upon the Bedford Canyon formation in the Santa Ana Mountains is a great thickness of slightly metamorphosed agglomerates, breccias, tuffs, and flows of andesitic to quartz latitic composition. These are the Santiago Peak volcanics (Larsen, 1948, pp. 22-27). Associated with them, and perhaps related to them, are hypabyssal intrusive masses of fine- to medium-grained, dominantly porphyritic rocks.

Plutonic masses of granodiorite and tonalite (quartz diorite), known as the Stonewall granodiorite (Hudson, 1922, pp. 191-193), are prominent in the area south of Lake Henshaw. Associated with these intrusive masses are highly irregular bodies of injection gneiss and other migmatitic rocks, which were formed by the addition of igneous material to the Julian schist.

The youngest and by far the most widespread of the rocks that lie beneath the great unconformity are plutonic types that represent the southern California batholith (Larsen, 1948, 1954), a huge composite mass that underlies much of the region. These rocks range in composition from gabbro to granite, but tonalites are most abundant. The individual intrusive bodies range from plutons of gabbro, tonalite, or granodiorite that are several miles in maximum exposed dimension (Map 10) to thin dikes of pegmatite and aplite (figs. 11, 12). In general the succession of intrusions appears to have been gabbro → basic tonalite → tonalite → granodiorite → quartz monzonite → granite; various dike rocks were emplaced during several different stages.

The batholith is thought to be of early Upper Cretaceous age, mainly on the basis of stratigraphic evidence in Baja California (e.g., Woodford and Harriss, 1938). It probably was formed from a slowly differentiating parent magma of gabbroic composition (Larsen, 1948, pp. 132-172). Successive injections of this magma probably accompanied episodes of local to regional diastrophism, and yielded many large and relatively uniform bodies of gabbroic to granodioritic rock, as well as smaller bodies of rocks that represent a wider range of composition.

Younger Rocks. The rocks that lie above the great unconformity of late Mesozoic age are mainly clastic sedimentary types. These are dominantly marine in the coastal areas and almost wholly nonmarine in the interior parts of the region. The oldest units in the sequence are exposed in and adjacent to the Santa Ana Mountains, where the basal part of the section consists of Upper Cretaceous formations that are chiefly marine (Dickerson, 1914; Packard, 1916; Popenoe, 1941, 1942; Woodring and Popenoe, 1945). These are overlain unconformably by marine and nonmarine strata of Paleocene and Eocene age (English, 1926; Woodring and Popenoe, 1945), which in turn are overlain by terrestrial beds of probable Oligocene age. This nonmarine sequence grades upward into, and is in part intertongued with, a section of marine beds that has been referred to the lower Miocene Vaqueros formation (Loel and Corey, 1932).

The younger marine strata are much more widely distributed, and appear in numerous hills that lie within and around the Los Angeles Basin (fig. 2). They form a thick section of middle Miocene to early Pleistocene age (Daviess and Woodford, 1949; Eldridge and Arnold,

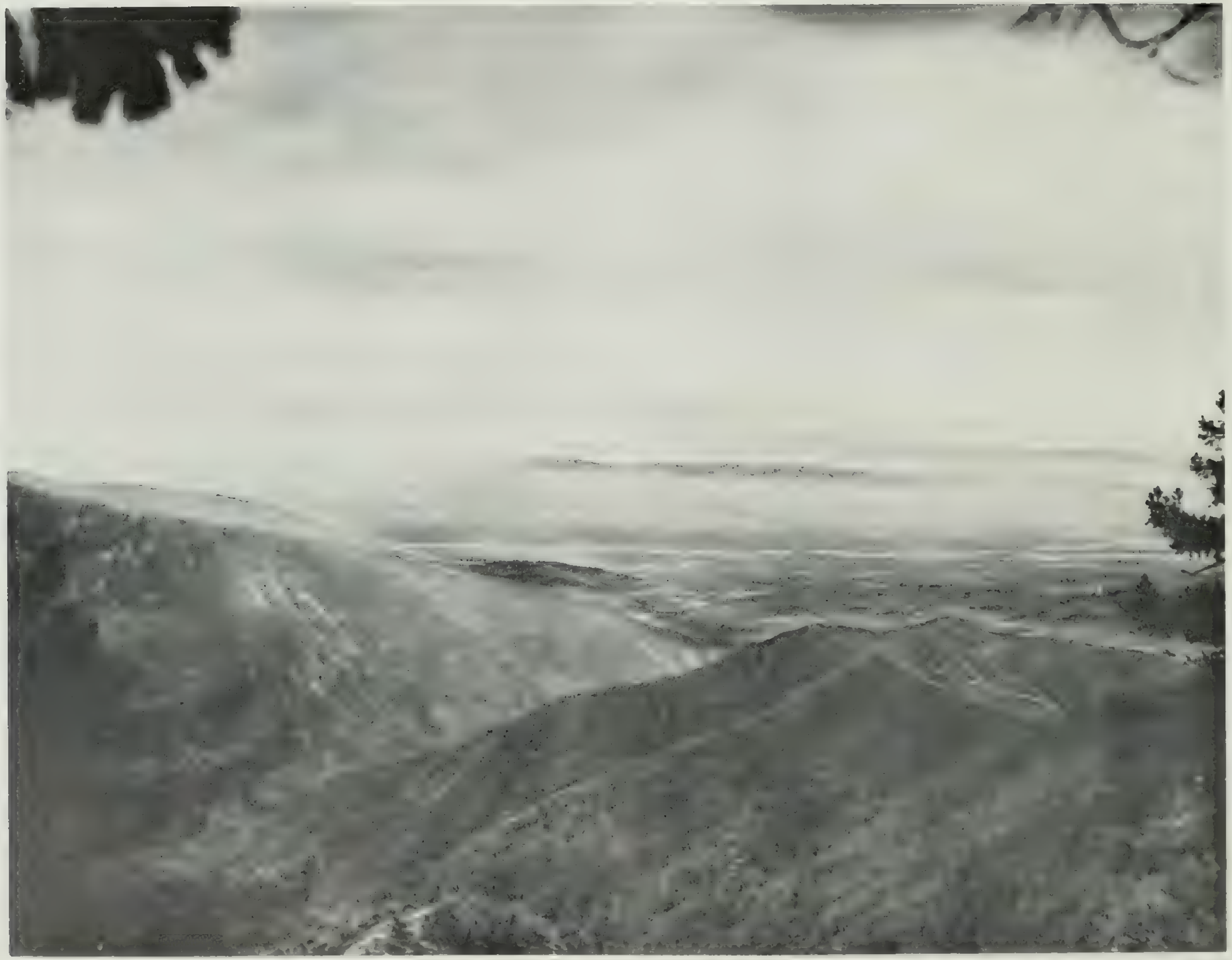


FIGURE 2. Southeastward view of the San Gabriel Valley from Mt. Wilson, in the San Gabriel Mountains, 1905. The San Gabriel River traverses a broad alluvial plain in the near part of the valley, and the San Jose Hills and Puente Hills rise above the haze-shrouded valley floor in the middle distance. The Santa Ana Mountains, dominated by Santiago Peak, appear beyond the lowland area, and on the distant skyline slightly to the left are the Agua Tibia Mountains. *Courtesy of Mt. Wilson and Palomar Observatories.*

Figure 3. Structure section across a part of the Los Angeles basin from the Palos Verdes Hills northeastward to the Puente Hills. *Modified slightly from Schoellhamer and Woodford (1951).*

1907; Kundert, 1952; Schoellhamer, et al., 1954; Woodford, et al., 1944), and are overlain in the lowland areas by fine- to coarse-grained nonmarine deposits of Quaternary age. Volcanic rocks are present in the middle Miocene part of the section (Shelton, 1946, 1954); these are mainly pyroclastic, and are andesitic and basaltic in composition.

The geology of the younger rocks in the Los Angeles Basin and adjoining areas has been summarized by Driver (1938) and by Woodford, et al. (1954), and numerous specific features of occurrence are discussed farther on in this guide. Stratigraphic relations, thicknesses, and brief lithologic descriptions are recorded in table 1.

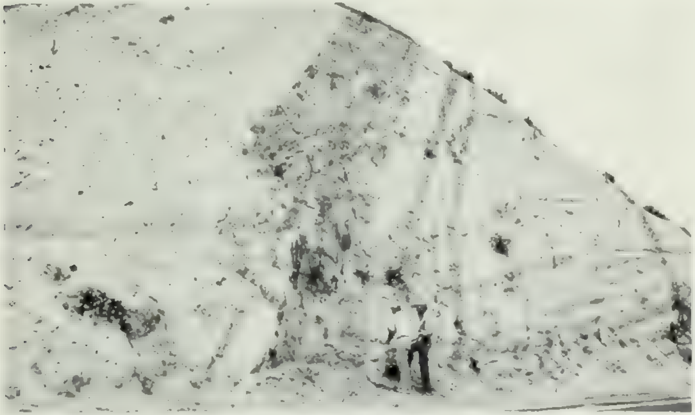


Figure 4. Roadcut exposure of the lower Pliocene Repetto formation at the southeast end of the Chino Hills, near Prado Dam. Intertongued siltstone (dark) and conglomerate sandstone (light) are locally disturbed in a way that suggests submarine slumping and sliding during the general period of deposition. Note the broken-off masses of siltstone in the bed of pebble conglomerate about 12 feet to left of the men.

The oldest known Cenozoic rocks of the interior areas are nonmarine Miocene strata that crop out along the margins of the Coachella and Imperial Valleys (Dibblee, 1954), as well as locally in the area north of San Jacinto. These are overlain by fluviatile and lacustrine beds of Pliocene age, which are referred to as the Mount Eden and San Timoteo formations in the area west and northwest of the San Jacinto Mountains (Axelrod, 1937, 1950; Fraser, 1931; Frick, 1921, 1933, 1937). Nonmarine deposits of Pleistocene age are more widespread, and include the Bautista beds of the San Jacinto River Valley and nearby areas (Frick, 1921; Fraser, 1931) and the Temecula arkose of the Elsinore-Temecula Valley (Mann, 1951). Like the Pliocene deposits, these consist in part of fine- to medium-grained, poorly consolidated sediments that were laid down in separate valleys and basins, and in part of very coarse-grained, moderately well-consolidated fanglomerates that represent old alluvial aprons formed along steep mountain fronts.

Sediments of late Pleistocene and Recent age are even more widespread, and include fanglomerates, stream-terrace gravels, lacustrine silts, and modern swamp, alluvial-fan, and flood-plain deposits. Late Tertiary or Quaternary volcanism in the Murrieta-Temecula area is attested by several remnants of olivine basalt flows that appear mainly as mesa cappings.

The geology of the younger rocks in the interior areas of the province has been summarized in greater detail elsewhere in this volume (Jahns, 1954), and their stratigraphic relationships in the area between Corona and Lake Henshaw are outlined in table 2.

Structure

In broad structural terms, the northern part of the Peninsular Range province is an uplifted and southwesterly tilted mass that is separated into several large, elongate, northwest-trending blocks by subparallel faults. These blocks are further sliced by lesser faults, and most are also segmented by cross faults. Both dip-slip and strike-

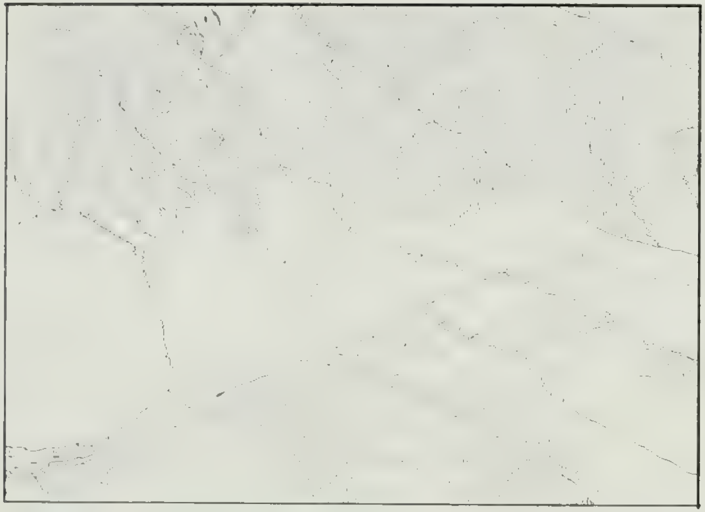


FIGURE 5. Westward view of a part of the Temescal trough, showing the steep lower slopes of the Santa Ana Mountains. The trace of the Glen Ivy South fault lies at the base of this scarp, and the trace of the Glen Ivy North fault is marked by a distinct linear scarplet that trends diagonally across the view. This scarplet, developed in Quaternary alluvial-fan deposits, faces southwestward against the general direction of drainage on the valley floor. Sketched from an air photograph.

slip (lateral) components of movement have been recognized along most of the breaks, and several of the master faults show evidence of major right-lateral displacements. Determination of the direction and amount of net slip on any of these breaks, however, remains an unsolved problem at the present time.

Most of the principal faults appear to have been intermittently active during large parts of Cenozoic time, and have had an important influence on the distribution, thickness, and lithology of the younger sedimentary rocks. Adjacent fault blocks commonly have had contrasting histories, which has complicated the problems of stratigraphic correlation, especially in the interior parts of the province. Some of the faults may well date back to late Mesozoic or earlier times, but the effects of pre-Cenozoic movements are difficult to distinguish from those of later movements.

Folding has been distinctly subordinate to faulting in most areas, and even the regional structure of the pre-Cretaceous rocks is deceptively simple. In nearly all large areas of exposure the metamorphic rocks are essentially homoclinal, with prevailingly northwest to north-northwest trends and steep southwest dips or moderate to steep

Table 1. Generalized stratigraphic column for the northern and eastern parts of the Los Angeles Basin and adjacent parts of the Santa Ana Mountains (see Maps 1-3) (in large part after Woodford et al., 1954).

AGE				MAP SYMBOL	ROCK UNIT		GENERAL THICKNESS (FEET)		LITHOLOGY
CENOZOIC	QUATERNARY	Recent		Qal	Alluvium		0–150		Gravel, sand, and silt of alluvial-fan and flood-plain origin.
		Pleistocene	Upper	Qft	Older alluvial fill and terrace deposits		0–1,700		Gravel, sand, and silt, poorly consolidated; commonly reddish and weathered.
			Lower	Qm	Fanglomerate		0–300+		Conglomerate and subordinate sandstone, locally well consolidated.
	TERTIARY	Pliocene	Upper	Tpu	Upper Pliocene deposits		1,700		Siltstone, conglomerate, and subordinate sandstone; marine.
			Lower	Tr	Repetto		600–4,500		Siltstone, with subordinate sandstone and conglomerate; marine.
		Miocene	Upper	Tpsc	Puente formation	Sycamore Canyon member	11,000 maximum	1,300	Interbedded conglomerate, micaceous siltstone, and sandstone; marine.
				Tpy		Yorba member		650	Thin-bedded gray siltstone, diatomaceous siltstone, and local sandstone and conglomerate; marine.
				Tpsq		Soquel member		1,650	Massive to well-bedded, coarse to gritty feldspathic sandstone; marine.
				Tplv		La Vida member		1,200	Gray to black, laminated siltstone, with interbedded feldspathic sandstone; marine.
			Middle	Tvol	Volcanic rocks		0-3,500		Extrusive and intrusive andesite and basalt, with abundant tuffs and breccias.
				Tt	Topanga formation		2,000		Conglomerate, sandstone, siltstone, and shale; mainly marine.
			Lower	Tvs	Vaqueros formation		3,000		Gray to buff sandstone, conglomerate, and local greenish gray sandy siltstone; marine.
		Oligocene and upper Eocene(?)			Sespe formation				Gray and variegated feldspathic sandstone, conglomerate, and siltstone; almost wholly nonmarine.
		Paleocene		Tsi	Silverado formation		1,400		Nonmarine conglomerate, sandstone, clay, and lignite, overlain by yellowish green to buff marine sandstone.
MESOZOIC	UPPER CRETACEOUS			Klh	Ladd formation*	Holz shale member	1,850		Dark gray to black shale and siltstone, with subordinate sandstone and conglomerate; marine.
				Klbc		Baker Canyon conglomerate member	1,500		Interbedded coarse conglomerate and feldspathic sandstone; marine.
	JURASSIC OR CRETACEOUS			JKp	Plutonic rocks that may represent the southern California batholith				Chiefly granodiorite and tonalite, with subordinate gneissic rocks.
	JURASSIC			Jsp	Santiago Peak volcanics		8,000+		Slightly metamorphosed agglomerates, breccias, tuffs, and flows of andesitic to quartz latitic composition; includes some related hypabyssal intrusive masses.
	TRIASSIC			Trbc	Bedford Canyon formation		20,000±		Slightly metamorphosed argillite and slate, with subordinate quartzite and local lenses of limestone and conglomerate; marine.

* This unit is both overlain and underlain by other formations of Upper Cretaceous age elsewhere in the Santa Ana Mountains.

Table 2. Generalized stratigraphic column for the part of the Peninsular Range province between Corona and Lake Henshaw (see Maps 4-8).

AGE			MAP SYMBOL	ROCK UNIT	GENERAL THICKNESS (Feet)	LITHOLOGY
CENOZOIC	QUATERNARY	Recent	Qal	Alluvium	0–60	Gravel, sand, silt, and clay of alluvial-fan, flood-plain, swamp, and lacustrine origin.
		Pleistocene	Qft	Basin fill and terrace deposits	0–550	Gravel, sand, and silt, poorly consolidated; includes coarse fanglomerate and chaotic breccia in some areas; nonmarine.
			Qwa	Arkose of Warner basin	0–600+	Micaceous arkose and feldspathic sandstone, poorly consolidated, with local interbedded siltstone, marl, and white tuff; nonmarine.
			Qta	Temecula arkose	0–3,700	
	TERTIARY	Pliocene	TQb	Basalt	20–110	Dark gray olivine basalt, in flows that cap several mesas.
			TQa	Older arkose	0–60	Micaceous arkose and conglomerate; may correspond to lower part of Temecula arkose.
			Tr	Repetto formation	3,000±	White to buff sandstone, siltstone, and conglomerate; marine.
		Miocene, Upper	Tp	Puente formation	5,000±	Siltstone, sandstone, conglomerate, and diatomaceous sandstone; marine.
		Miocene, Lower	Tvs	Vaqueros formation	2,300	Sandstone, conglomerate, and greenish gray siltstone; marine.
		Oligocene and upper Eocene ?		Sespe formation		Gray to variegated sandstone, arkose, and conglomerate; nonmarine.
		Paleocene	Tsi	Silverado formation	4,000±	Siltstone, feldspathic sandstone, and conglomerate, with clay and lignite in lower part; partly nonmarine and partly marine.
MESOZOIC	UPPER CRETACEOUS		Klh	Ladd formation* Holz shale member	1,850	Dark gray to black siltstone and shale, with subordinate sandstone and conglomerate; marine.
			Klbc	Baker Canyon conglomerate member	1,500	Interbedded coarse conglomerate and feldspathic sandstone; marine.
	CRETACEOUS		Kgd	Granodiorite, quartz monzonite, and granite	Intrusive rocks of the southern California batholith	Light to medium gray, fine- to coarse-grained felsic rocks; inclusions locally abundant.
			Kt	Tonalites		Light to medium gray, medium- to coarse-grained rocks; inclusions very abundant in some areas.
			Kgb	Gabbroic rocks		Norites and gabbros that vary considerably in composition and texture.
	JURASSIC ?		Js	Stonewall granodiorite and related gneisses	Intrusive and hybrid rocks that antedate the southern California batholith	Medium gray, medium- to coarse-grained intrusive rock, with associated hybrid gneisses derived from Julian schist.
			Jgp	Granodiorite porphyry and quartz monzonite porphyry		Medium to dark gray, fine- to medium-grained, even-grained to porphyritic rock.
			Jtw	Temescal Wash quartz latite porphyry		Dark gray, fine- to medium-grained porphyritic rock with locally abundant inclusions.
			Jsp	Santiago Peak volcanics	8,000+	Slightly metamorphosed agglomerates, breccias, tuffs, and flows of andesitic to quartz latitic composition; volcanic conglomerate at base.
	TRIASSIC		TRbc	Bedford Canyon formation (includes Julian schist and other rocks that may be in part older)	20,000±	Slightly metamorphosed argillite and slate, with abundant quartzite and local lenses of limestone and conglomerate; includes mica schists and amphibole schists in southern part of area; marine.

* This unit is both overlain and underlain by other formations of Upper Cretaceous age on the southwestern side of the Santa Ana Mountains.

northeast dips. Few large folds can be recognized, but the rocks have been considerably broken, sheared, and contorted in detail. All appear to have been deformed and metamorphosed prior to emplacement of the southern California batholith, and many of them also show the effects of later contact metamorphism attendant upon this episode of igneous intrusion. Both the igneous and the metamorphic rocks have been converted into flaser gneisses and mylonites along some major zones of shearing.

The younger rocks have been compressed into numerous open folds whose flanks are complicated in places by faults, unconformities, or by minor wrinkles and bulges. Most of the large folds trend west-northwest to north-northwest, and appear to be genetically related to faults that lie beneath or adjacent to them. Indeed, the younger sedimentary sections in many of the basins can be regarded as moderately wrinkled and ruptured blankets that conceal a much more severely disturbed terrane of older rocks.

Numerous episodes of deformation are recorded by unconformities in the Cenozoic section, particularly around the margins of the sedimentary basins. In the Santa Ana Mountains, Paleocene deposits rest upon an ancient surface of erosion that truncates tilted and folded strata of Upper Cretaceous age, as well as older igneous and metamorphic rocks. Much of Oligocene and lower Miocene time must have been characterized by widespread erosion and local deposition, which

FIGURE 6. Fresh exposure of lignite and clay in upper pit at the Alberhill clay mine. The coaly bed above the man is overlain by light-colored, blocky clay, and is underlain successively by gray high-alumina clay with conchoidal fracture and by pinkish, dark-appearing clay that is in part of residual origin. All of the exposed material is in the lower part of the Paleocene Silverado formation.

were interrupted in middle Miocene time by major pulses of faulting and uplift that caused fundamental changes in the pattern of drainage and the sizes and shapes of the sedimentary basins. Additional pulses of milder deformation followed during upper Miocene and Pliocene time. Severe diastrophism in late Pliocene and middle Pleistocene times is demonstrated by major unconformities in both marine and nonmarine sections. Much of the present landscape was developed during the widespread middle Pleistocene orogeny, and deformation in many areas has continued to the present time.

Geomorphology

The geomorphic history of the region is intimately related to the history of movements within and between the major fault blocks during late Cenozoic time. Many features of the modern landscape owe their gross form and position more to recent diastrophism than to the effects of erosion on contrasting types of rocks, but the known interplay of diastrophism and erosion ordinarily is difficult to resolve in detail.

In the higher interior areas are unusual (and commonly anomalous) combinations of prominent ridges and peaks (figs. 2, 21, 22), broad erosion surfaces of low relief (fig. 21), narrow and steep-walled canyons (fig. 22), longitudinal trenches, benches, and valleys that are defined by zones of faulting (figs. 11, 22), and many wide valleys and basins (figs. 2, 19). The broad upland surfaces appear at various levels, and have prompted much argument as to whether they are parts of a single, once-extensive surface of erosion that was dislocated by faulting in Quaternary time (e.g., Bryan and Wickson, 1931; Miller, 1935), whether they were formed independently at different levels (Sauer, 1929) and perhaps at different times, or whether some of them are older features that have been exhumed from beneath a cover of younger Cenozoic rocks (Dudley, 1936). Several of these surfaces show evidence of Quaternary upwarping, and several of the shallow basins appear to have been bowed downward during late Quaternary time.

Recent alluvial fans are impressive features of the lowland areas, and remnants of even more extensive Pleistocene fans are widely preserved (figs. 11, 17). Many of these can be correlated with gravel-veneered fluviatile terraces in adjacent canyons and valleys. Recent uplift in the coastal areas is attested by wave-cut marine terraces, some of which have been warped, tilted, or offset slightly by faulting. Several anticlinal folds in the Los Angeles Basin have been formed so recently that their structure is reflected by the present topography, and the uplift of some evidently was so rapid that pre-existing streams were unable to breach them. Others are cut by antecedent streams, and, on a much larger scale, the Los Angeles, San Gabriel, and Santa Ana Rivers may well be antecedent to the uplift of the Santa Monica Mountains, Repetto Hills, and Santa Ana Mountains. Recent movements along faults are evidenced in several parts of the region by scarplets in alluvium, sag ponds, anomalies in stream profiles, offset drainage lines, and by historic records of numerous earthquakes.

Economic Features

By far the most important natural resources in the region are soil, water, and petroleum. Extensive settlement and agricultural development in many areas have led to full use of available sources of both surface water and ground-waters, and during recent decades it has become necessary to import increasing quantities of water from sources in other regions.

The sedimentary deposits of the Los Angeles basin have yielded an enormous amount of petroleum, as well as sand and gravel, brick clays, foundry and other specialty sands, diatomite, non-swelling bentonite, and iodine that is recovered from oil-field brines. Tertiary strata elsewhere in the region have been worked commercially for glass sand, fire clay, china clay, gypsite, lignite, and optical-grade calcite.

The rocks of the southern California batholith have been quarried for dimension stone, aggregate, or rip rap in many areas, and the pegmatite deposits of Riverside and San Diego Counties have yielded commercial feldspar, quartz, and lithium minerals in addition to the gem minerals for which they are best known. Deposits of amphibole asbestos and magnesite occur in small bodies of altered ultrabasic rock in the San Jacinto Mountains and areas adjacent on the west.

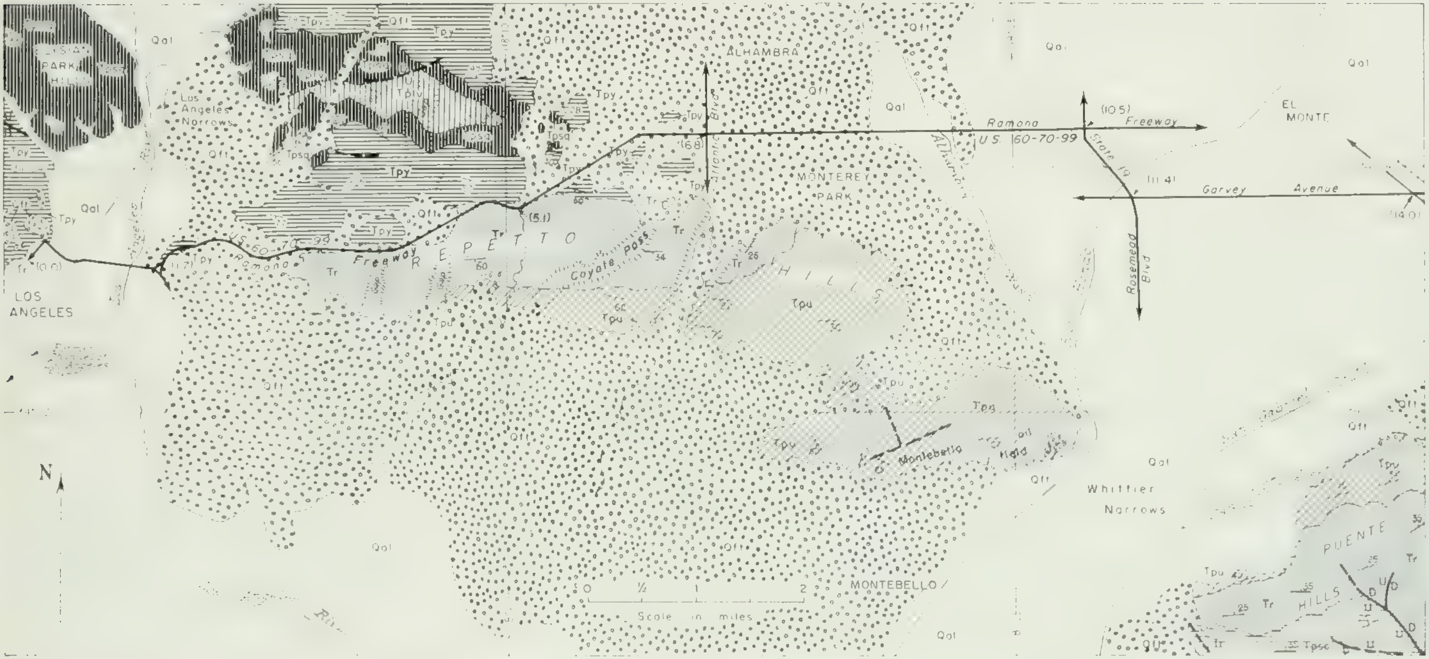
The pre-batholith rocks supply very large quantities of limestone for cement making, as well as the raw material for a substantial production of roofing granules. Vein deposits in both igneous and metamorphic rocks have been mined in several districts for gold, lead, zinc, copper, and tungsten, and with less success for nickel, tin, and molybdenum. Most of these districts are noted in the following road-log descriptions.

ROAD LOGS

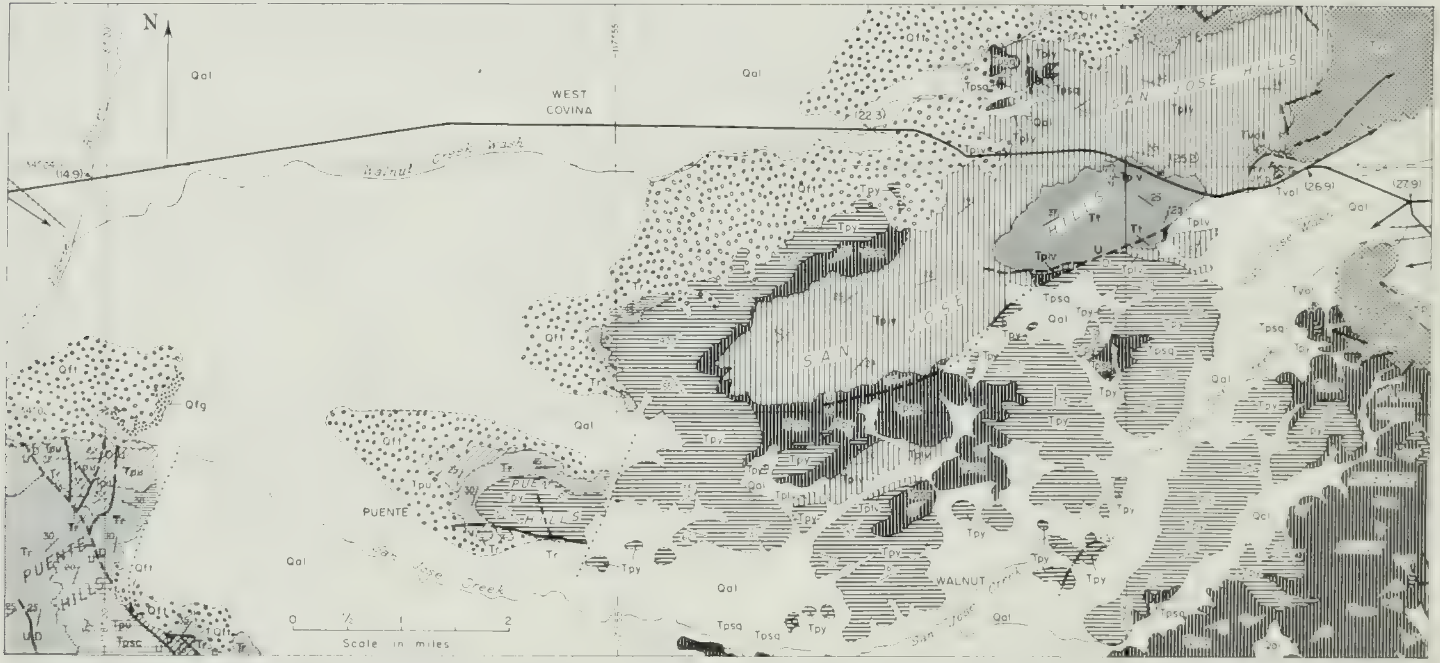
Los Angeles to Pomona—30.4 Miles

(Maps 1, 2, 3; Table 1)

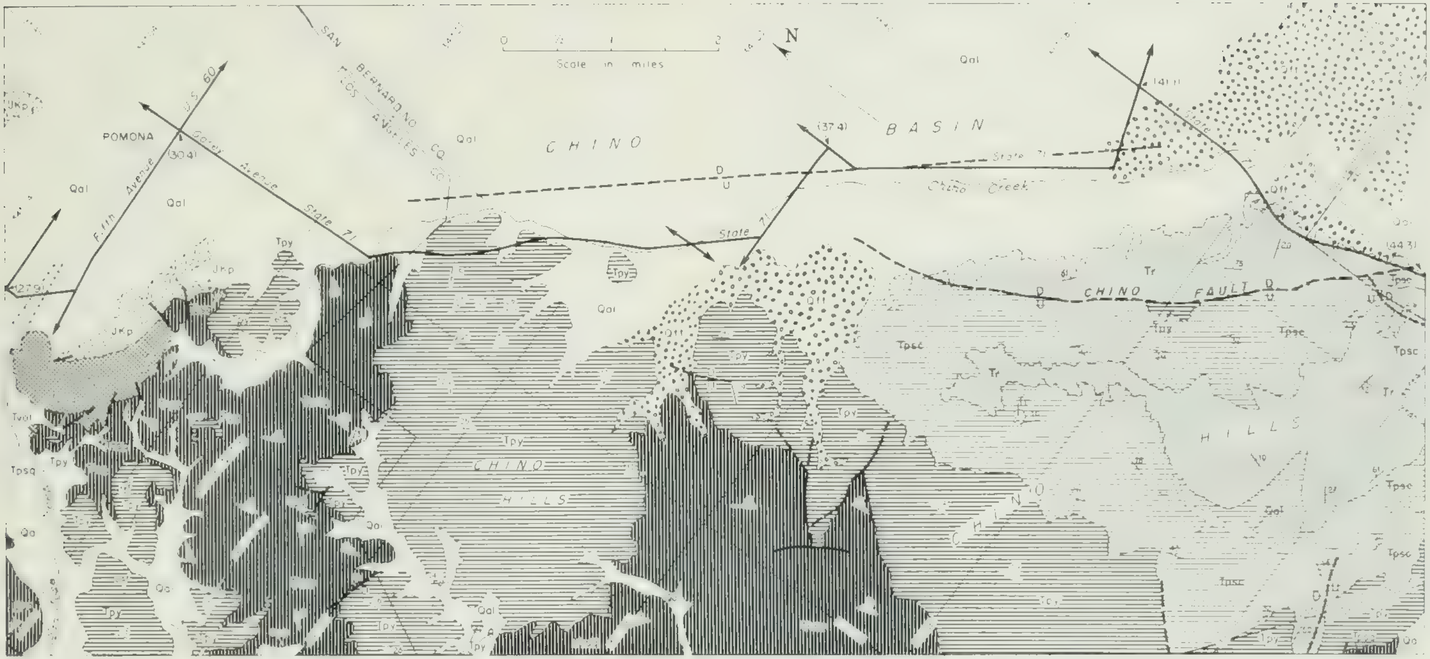
The Los Angeles Basin. The lowland area that lies between the Pacific Ocean on the southwest and the Santa Monica Mountains, the elongate Repetto and Puente Hills, and the Santa Ana Mountains on the northeast is known geographically as the Los Angeles Basin (fig. 1). It is about 50 miles long, as measured in a northwest-southeast direction, and about 20 miles wide. Northwest of it lies the San Gabriel Valley, from whose broad floor rise additional elongate hills



Map 1. Los Angeles to El Monte. Qal—alluvium; Qft—older alluvial deposits; Tpu—upper Pliocene deposits; Tr—Repetto formation; Tpsc—Sycamore Canyon member of Puente formation; Tpy—Yorba member of Puente formation; Tpsq—Soquel member of Puente formation; Tplv—La Vida member of Puente formation. See Table 1 for stratigraphic relationships and descriptions of these geologic units. *Geology after Woodford, et al. (1954).*



Map 2. El Monte to San Jose Hills and Pomona. Qal—alluvium; Qft—older alluvial deposits; Qfg—fanglomerate; Tpu—upper Pliocene deposits; Tr—Repetto formation; Tpsc—Sycamore Canyon member of Puente formation; Tpy—Yorba member of Puente formation; Tpsq—Soquel member of Puente formation; Tplv—La Vida member of Puente formation; Tvol—volcanic rocks; Tt—Topanga formation; JKp—plutonic igneous rocks. See Table 1 for stratigraphic relationships and descriptions of these geologic units. *Geology after Woodford, et al. (1954).*



Map 3. Pomona to Prado Dam. Qal—alluvium; Qft—older alluvial deposits; Tr—Repetto formation; Tpsc—Sycamore Canyon member of Puente formation; Tpy—Yorba member of Puente formation; Tpsq—Soquel member of Puente formation; Tvol—volcanic rocks; JKp—plutonic igneous rocks. See Table 1 for stratigraphic relationships and descriptions of these geologic units. *Geology after Woodford, et al. (1954).*

(fig. 2). These two areas contain the greatest concentration of population in the State.

The Los Angeles Basin marks the site of a more extensive trough of middle and late Cenozoic sedimentation to which the name Los Angeles basin has been attached in a purely geologic sense. Both marine and nonmarine deposits were laid down in parts of this area during late Cretaceous and early Tertiary time, but it was first defined as a single broad trough in middle Miocene time, when its irregular surface was completely covered by a widespread marine embayment. As the basin gradually subsided, to a much greater extent in some places than in others, it received considerable thicknesses of marine sediments. Some parts of it were filled to points above sea level by early Pleistocene time, and from then on marine sediments were deposited mainly in its southwestern parts.

The Cenozoic section of the Los Angeles basin is 10,000 feet or more thick in all but the marginal areas, and geophysical evidence indicates a thickness of slightly more than 40,000 feet in the central deep, southwest of the Puente Hills (fig. 3). In this area the Pliocene section alone is more than 10,000 feet thick. The basin filling is dominantly fine to medium grained and clastic, but it represents a great variety of sedimentary environments, particularly in areas that lay along and near the margins of the embayment. These and other stratigraphic features have been summarized by Driver (1948), Woodford, et al. (1954), and others.

The 40 oil fields in the Los Angeles basin have yielded more than 4 billion barrels of petroleum since 1880, which accounts for more than two-fifths of the production from the entire State. Average recovery in the proved fields has amounted to more than 100,000 barrels per acre, a remarkable performance that reflects the richness of the accumulations, together with the occurrence of producing zones at more than one stratigraphic level in most of the fields.

Most of the known accumulations are in strata of early Pliocene and late Miocene age, and the remainder of the production is obtained from upper Pliocene and middle Miocene strata, and from fractured masses of older rocks. More than half of the oil produced thus far has been extracted from two series of en echelon faulted anticlines that extend northwestward across the basin (fig. 3). The remainder has been obtained from other anticlines, fault traps, and stratigraphic traps, chiefly in areas near the margins of the basin.

0.0 Start of trip. Los Angeles Civic Center.

From First Street drive northeastward on Spring Street or Broadway to Hollywood Freeway. Ahead and to left (north-northwest) is Fort Moore Hill, which consists of upper Miocene marine siltstone and sandstone (Puente formation) capped by reddish brown Quaternary gravels. The Miocene strata dip southward, and in downtown Los Angeles they are overlain conformably by marine strata of the lower Pliocene Repetto formation. Still farther south in the downtown area are upper Pliocene marine strata. All of these rocks lie on the south flank of the Elysian Park anticline, the axis of which extends through the northeastern part of the Elysian Park Hills and into the Repetto Hills east of the Los Angeles River (Map 1).

0.3 Turn right (southeast) onto Hollywood Freeway. The old Los Angeles Plaza lies about two blocks to the left (north). Continue past Los Angeles Union Station and cross floodplain of the Los Angeles River.

1.1 Bridge over Los Angeles River. About 1½ miles north of this point the river issues from the Los Angeles Narrows, whence it flows southward across a broad alluvial plain to discharge into the ocean near Long Beach. Its channel has shifted considerably during Recent time, and at least once in the recent past the river has flowed westward to empty into the ocean via an alternate channel now occupied by Ballona Creek (Map 1, fig. 1). The river probably is antecedent where it crosses the Elysian Park anticline in the narrows, as it appears to have maintained its course while this fold was developing in late Pliocene and Quaternary time.

1.3 Turn left (northeast) onto Ramona Freeway (U.S. 60-70-99).

1.7 Roadcut exposures of upper Miocene sandstone and gray to bluish gray siltstone (Yorba member of Puente formation), overlain by late Recent rubble.

3.5 City Terrace district. The freeway skirts the northern edge of the Repetto Hills, which are composed of light gray siltstone and subordinate sandstone, mudstone, and conglomerate that are characteristic of the Pliocene section in the northern part of the Los Angeles basin. These sedimentary rocks dip moderately to steeply southward. The hills on the north (left) side of the freeway are underlain by siltstone, diatomaceous shale, and coarser-grained sediments of the Puente formation (Yorba member).

Several of the roadcuts expose Quaternary gravels that occupy a basin-like area about half a mile in diameter; this depression is a part of a former line of drainage across the hills, and well-defined wind gaps lie both north and south of it (Map 1). The hills evidently were uplifted athwart the prevailing direction of drainage in this general area, probably in middle and late Pleistocene time. During its late stages this uplift must have been more rapid than the downcutting of several of the streams, which thus were forced to abandon the channels that they had cut during earlier stages of the uplift. At least four well-defined wind gaps, or passes, cross the Repetto Hills, and others are present in the hills to the northwest.

5.1 Bricks in yard on the right (south) are made from siltstone of the lower Pliocene Repetto formation. A few hundred feet north of the freeway is the conformable contact between this unit and the underlying Puente formation, three members of which are exposed in the hills to the northwest. They dip southward off the crest of an anticline that plunges gently to the east (Map 1).

5.3 Large roadcut exposure of Repetto strata.

5.4 Angular unconformity between Repetto formation and Quaternary gravels is revealed in the roadcut on right (south).

6.5 Edge of San Gabriel Valley. The hills that rise above the valley floor are underlain by fine-grained Puente strata. About a mile to the south is the head of Coyote Pass, a wind gap through the Repetto Hills.

6.8 Atlantic Boulevard. About a mile south of this point is the head of a gap through the Repetto Hills that was once occupied by a through-flowing stream, but was later abandoned and became a wind gap. It now is drained by a small, underfit, intermittent stream. Exposed along the west side of this gap is the type section of the lower Pliocene Repetto formation (Reed, 1932).

The Repetto section, about 2,500 feet thick in this area, consists chiefly of micaceous siltstone that rests conformably upon diatomaceous shales of the Puente formation. It contains an abundance of Foraminifera, many of which suggest deposition of the sediments in waters at least 4,000 feet deep (Natland, 1952). Conformably overlying the Repetto strata is a section of upper Pliocene siltstone, with subordinate sandstone and conglomerate. These beds, which underlie much of the eastern Repetto Hills, ordinarily are distinguished from the lithologically similar Repetto formation on the basis of their contained Foraminifera. They have been correlated by some geologists with the Pico formation of the Ventura basin, about 30 miles to the northwest, but the two units probably are only in part equivalent.

The upper part of the Pliocene section is featured in some areas by numerous isolated pebbles, as well as lenses of conglomerate in which shallow-water megafossils are preserved. The siltstone that encloses these pebbles and lenses contains Foraminifera characteristic of a deep-water environment. This anomalous association, together with abundant slickensides, contortion, and local kneading together of the rocks, suggest that masses of near-shore deposits were transported down slope into deeper waters by sliding or turbidity flows during deposition of the finer-grained parts of the section.

San Gabriel Mountains. North of the Ramona Freeway the floor of the San Gabriel Valley extends gradually upward toward the bold south face of the San Gabriel Mountains, 8 to 10 miles distant. This east-trending mountain mass is a major element of the Transverse Range province, which bounds the Peninsular Range province on the north. It is lens-shaped in plan, is about 60 miles long, and rises to general altitudes of 5,000 to 9,000 feet. On clear days Mt. Wilson, with its observatory buildings and bristle of television transmission towers, is visible in a northerly direction.

The range is essentially a gigantic horst that is bounded on all sides by major faults, and consists of plutonic igneous rocks of late Mesozoic age, together with a very complex series of older intrusive and metamorphic rocks. It is transected by several large faults, and by countless shear and shatter zones. Its south face is defined by the Sierra Madre fault zone, a group of branching and en echelon breaks whose prevailing dip is northward beneath the mountains.

Intermittent uplift of the range probably took place during a large part of Tertiary time, and this great mass doubtless contributed much sedimentary material to the Los Angeles basin. The last major uplift probably dates from middle Pleistocene time, and subsequent erosion has scored the range with numerous deep canyons. Higher parts of the range, which lie to the northeast, may mark an axis of broad transverse upwarping.

10.5 Turn right (south) onto Rosemead Boulevard (State Highway 19).

11.2 Bridge over Rio Hondo. The San Gabriel River, one of the major streams in the region, debouches onto the valley floor from the mouth of a steep-walled canyon about 11 miles to the northeast (fig. 1). It traverses a very large alluvial fan (fig. 2), on whose surface it splits into two channels. The more westerly of these, the Rio Hondo channel, drains south-

southwestward to join the Los Angeles River; the other, the San Gabriel channel, drains southward to the ocean at Seal Beach.

Both branches of the river flow through the Whittier Narrows, about 2½ miles to the south. This is a gap, nearly 2 miles in width, that separates the Repetto Hills from the Puente Hills farther east. It may well have been a channel-like feature in lower Pliocene time, as suggested by the distribution of coarse detritus in the Repetto formation (M. L. Natland, in Kundert, 1952, pp. 7-8), but its present form is the result of later trenching. A wide, alluvium-floored trough has been cut into older alluvium that was deposited in the narrows during late Pleistocene time.

Immediately west of the narrows is the Montebello oil field, in which oil is obtained from lenticular zones in the Repetto formation, and to a lesser extent from upper Miocene strata. The main structural element in this field is an eastward-plunging anticline, parts of which have been ruptured by faults.

11.4 Turn left (east) onto Garvey Avenue.

14.0 Five Points; cross Valley Boulevard.

14.9 Bridge over San Gabriel River. For the next few miles the road crosses a broad alluvial plain that slopes gently and uniformly southwest. To the south are the western Puente Hills, which are underlain by upper Miocene and Pliocene strata. A striking angular unconformity between upper Pleistocene gravels above, and lower Pleistocene and upper Pliocene strata below, is well exposed in the gorge cut by San Jose Creek through the northern tip of these hills.

The Whittier fault zone, a major structural feature of the Los Angeles basin, extends along the south flank of the hills as a series of anastomosing breaks. It dips northward, and has had several thousand feet of reverse movement (fig. 3). Evidence of large right-lateral displacements also has been recognized (Kundert, 1952; Woodford, et al., 1954), especially in areas farther east.

Several oil fields are present along the south side of the western and central Puente Hills. Most of the accumulations are related to the Whittier fault, and the subsurface structure of the fields is locally very complex.

22.3 Bridge over Walnut Creek Wash. For about a mile beyond this point the road traverses a dissected bench of reddish brown older alluvium that is known in this area as the San Dimas formation. It probably is late Pleistocene in age.

23.9 San Jose Hills. These hills are essentially an anticlinal mass of Miocene rocks, but their structure is complicated in detail by numerous faults and smaller folds. Most extensively exposed is the upper Miocene Puente formation, which in the Puente Hills has been divided into four members (Schoellhamer, et al., 1954). In ascending order, these are the La Vida, Soquel, Yorba, and Sycamore Canyon (table 1). The Yorba and Soquel members appear along the northwest margin and in the southern part of the San Jose Hills, and the La Vida member is exposed in their higher parts. Older rocks, chiefly the middle Miocene Topanga formation and volcanic rocks, crop out along the crest and in the northeastern part of the hills.

For the next mile, in the Covina Knolls section of the hills, are roadcut exposures of thin-bedded La Vida siltstone and sandstone. The effects of widespread recent slumping are clearly visible, and mass movements of these fine-grained rocks have been a serious problem to property owners in this area.

25.2 Crest of hills. The roadcuts expose pebbly sandstone and pebble to cobble conglomerate of the Topanga formation (Buzzard Peak conglomerate member), which is about 2,000 feet thick in this area. Conglomerate is interbedded with much finer-grained rocks in roadcuts beyond this point.

26.1 The highway here traverses an area of considerable landsliding, mainly involving fine-grained beds of the Puente formation (La Vida member). A large slide that once blocked the road was by-passed for several years. Attempts have been made to stabilize the larger slides by means of broad excavations and drainage of their source areas.

Preferential growth of prickly pear cactus outlines the general distribution of sandstone and conglomerate beds on the hillside to the north. To the south, the main mass of the Puente Hills is visible across the valley occupied by San Jose Wash.

26.6 Puddingstone Road. Middle Miocene volcanic rocks rest upon dacite porphyry, here inconspicuously exposed, and are overlain by La Vida strata. Similar dacite porphyry is intrusive into gneissic plutonic rocks of late Mesozoic age in a spur of these hills about 2 miles to the east-northeast.

26.9 Bear right (east) off freeway onto U. S. Highway 60.

Large roadcuts along the freeway expose light-colored, compact, thinly laminated tuff and fine-grained tuff breccia overlain by gently dipping volcanic breccia that is darker, much coarser grained, and contains abundant fragments of brownish to greenish gray flow rocks. These are parts of a thick volcanic series, known as the Glendora volcanics (Shelton, 1946), that crops out extensively in areas to the north. The rocks of this series are mainly andesitic in composition, and pyroclastic accumulations are dominant over intrusive and flow rocks. The formation is as much as 3,500 feet thick beneath Covina, about 5 miles to the west, where it has been penetrated by wells (Shelton, 1954).

The Glendora volcanics appear at or near the top of the Topanga formation in several areas, and probably are correlative with the volcanic rocks of middle Miocene age in the Santa Ana Mountains, Santa Monica Mountains, Palos Verdes Hills, and other areas within or near the Los Angeles basin.

27.9 Turn right (south) and continue on U. S. Highway 60, crossing railroad tracks on overpass. From this overpass a large quarry, developed in andesitic volcanic rocks, is visible to the right (southwest). Low on the slopes of the hills to the south, these rocks rest unconformably upon quartz diorite of late Mesozoic age.

28.6 Turn left (east) onto Fifth Avenue.

30.4 Pomona, Fifth and Garey Avenues.

Pomona to Corona—20.3 Miles
(Maps 3, 4; Table 1)

30.4 Pomona. Turn right (south) onto Garey Avenue (State Highway 71).

For the next 13 miles the route of travel follows the margin of the broad San Bernardino Valley, which is bounded on the southwest by a part of the Puente Hills known as the Chino Hills. These hills are composed mainly of northeasterly dipping upper Miocene strata. The adjacent part of the San Bernardino Valley has the structure of a narrow, elongate basin, the Chino basin, which is bounded on both sides by northwest-trending high-angle faults whose positions are outlined by sharp differences in ground-water levels. This basin contains at least 1,300 feet of Quaternary fluviatile deposits and several thousand feet of upper Tertiary marine strata (Woodford, et al., 1944). The basin and adjoining parts of the valley have been filled to the same general level by Recent alluvium derived from the San Gabriel Mountains to the north.

33.2 Sandstone and siltstone of the Puente formation (Yorba member) are exposed in roadcuts for 1.3 miles, beyond which the road traverses the valley floor. This part of the valley is used mainly for dairying and the raising of field crops.

36.4 Turn left (east) and continue on State Highway 71.

37.4 California Institution for Men. Turn right (south).

41.1 Turn right (south) onto Euclid Avenue Freeway (State Highway 71). From this point the highway crosses a low terrace of upper Pleistocene gravels before dipping into the shallow trench of Chino Creek. The eastern end of the Chino Hills lies ahead, and the Santa Ana Mountains rise steeply in the distance.

42.4 The freeway rises onto a dissected terrace of Quaternary gravels, beyond which it cuts through coarse-grained clastic strata of the Repetto formation. This formation is finer grained farther south, where roadcuts expose siltstone with abundant light-colored, cobble-size concretions.

44.2 The freeway crosses the Chino fault, a steeply dipping reverse fault that separates Repetto strata on the northeast from finer-grained Puente strata on the southwest.

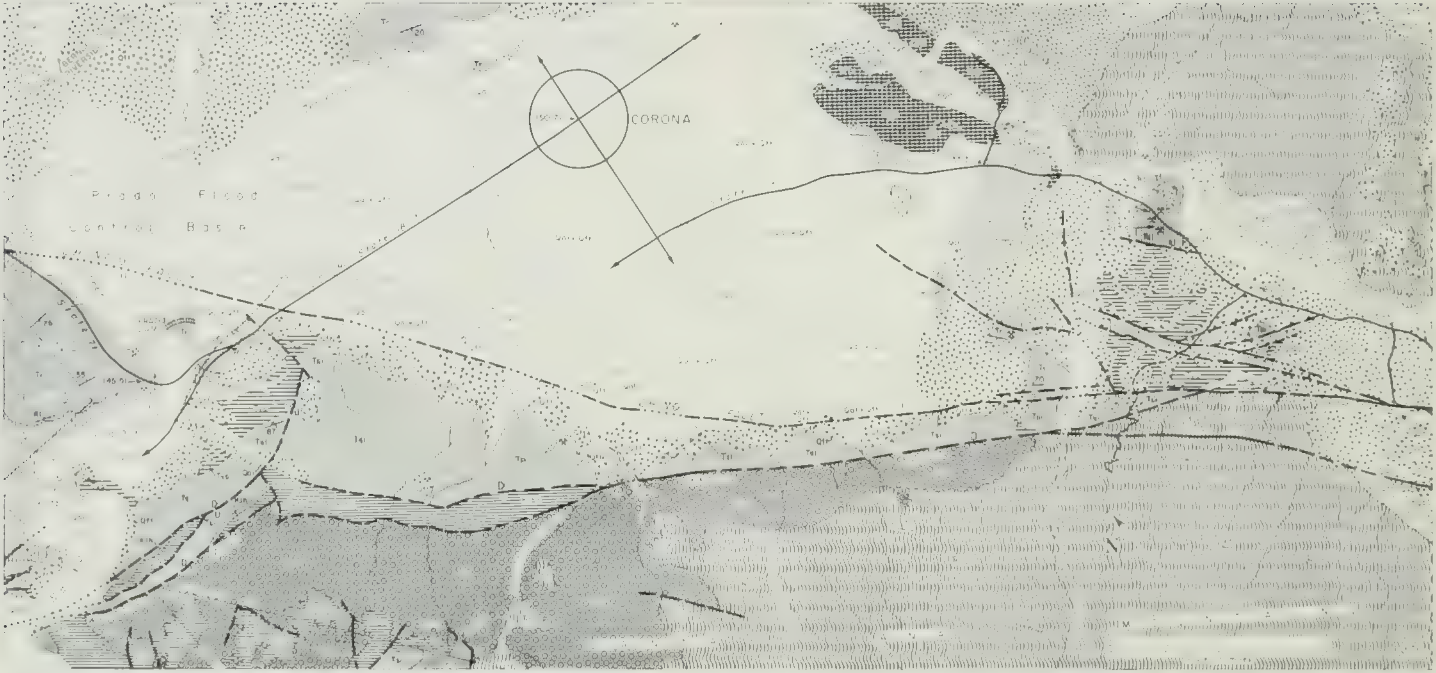
44.3 Large roadcut exposures of steeply dipping siltstone, sandstone, and conglomerate of the Puente formation (Sycamore Canyon member). The siltstone contains many calcareous concretions, and the fine-grained, dark-colored beds have been contorted on a small scale by slumping.

This upper Miocene section is overlain by Repetto strata in the small canyon immediately to the south. Both formations lie on the northeast flank of the Arena Blanca syncline, a large asymmetric fold that plunges southeast and is truncated by the Chino fault.

45.1 Cliffs of Repetto sandstone and conglomerate. Lenticular bedding, cut-and-fill structure, and sandstone dikes are prominent; only the thin beds of siltstone are continuous and of uniform thickness.

45.4 Axial region of the Arena Blanca syncline. The beds dip very steeply, and the trough of the fold evidently has been wrinkled sharply downward.

45.7 Steeply dipping Repetto strata in deep roadcuts. Siltstone, sandstone, and conglomerate are intertongued in a complex way, and some of the relations suggest submarine slumping and sliding (fig. 4). These beds continue east-southeastward



Map 4. Prado Dam to Glen Ivy. Qal—alluvium; Qft—older alluvial deposits; Tr—Repetto formation; Tp—Puente formation; Tt—Topanga formation; Tvs—Vaqueros and Sespe formations, undivided; Tsi—Silverado formation; Klh—Holz shale member of Ladd formation; Klbc—Baker Canyon conglomerate member of Ladd formation; Kgd—granodiorite, quartz monzonite, and granite; Kt—tonalite; Kgb—gabbro and norite; Jgp—granodiorite porphyry and quartz monzonite porphyry; Jtw—Temescal Wash quartz latite porphyry; Jsp—Santiago Peak volcanics; TRbc—Bedford Canyon formation. See Table 2 for stratigraphic relationships and descriptions of these geologic units. *Geology after Gray (1954), Larsen (1948), and Woodford, et al. (1954); modified by R. H. Jahns.*

across the canyon of the Santa Ana River, and can be seen in large roadcuts on the opposite side.

45.9 Prado Dam. Visible in a southerly direction from this point are the rugged northeast face of the Santa Ana Mountains, a bordering lowland area of great structural complexity, and the head of Santa Ana Canyon (Map 4). Low on the main slope of the Santa Ana Mountains, the Whittier fault zone butts against or merges into the Elsinore fault zone, which extends southeastward beyond this area for a distance of at least 125 miles. The Chino fault, whose trace lies about a mile northeast of the view point, represents the northwestern extension of the Elsinore fault zone.

Exposed in the longest roadcut to the southeast, on the opposite side of Santa Ana Canyon, is the very steep, northeast-dipping contact between the Repetto formation and the underlying Puente formation, which in this area is only about 1,000 feet thick. Nonmarine strata of the Oligocene (?) Sespe formation are poorly exposed beyond the first main ridge above the roadcut, and farther in the distance is a much dissected area, not visible from this point, that is underlain by the Paleocene Silverado formation (Map 4; tables 1, 2). A fault slice of Upper Cretaceous strata separates the Tertiary section from the Jurassic (?) Santiago Peak volcanics, on which the main slope of the mountains has been developed. Preserved on the highest ridge that appears along the skyline are erosional remnants of Upper Cretaceous strata that rest unconformably on the metavolcanic rocks.

Santa Ana Canyon was cut by the Santa Ana River during Quaternary time, and remnants of a once-continuous apron of upper Pleistocene alluvial gravels are clearly preserved in terrace segments on the south side of the canyon. The river is thought to have flowed through this area prior to the last major uplift of the mountain mass, and to have maintained its course by downcutting during the uplift. It has been suggested (English, 1926, p. 65) that the river may have been deflected slightly in a northward direction by the core of hard crystalline rocks in the range.

Prado Dam is an earth-fill structure built for flood-control purposes by the U. S. Army Corps of Engineers. It is 2,280 feet long and 106 feet high.

46.9 Grade separation. Continue on State Highway 71 and cross Santa Fe railroad tracks.

47.6 Junction with U. S. Highway 91. Continue eastward across a series of large alluvial fans into Corona. Located in an area of citrus groves, Corona is known as "the Circle City" because one of its main streets describes a perfect circle, 0.9 mile in diameter. This street was used for horse and automobile racing many years ago.

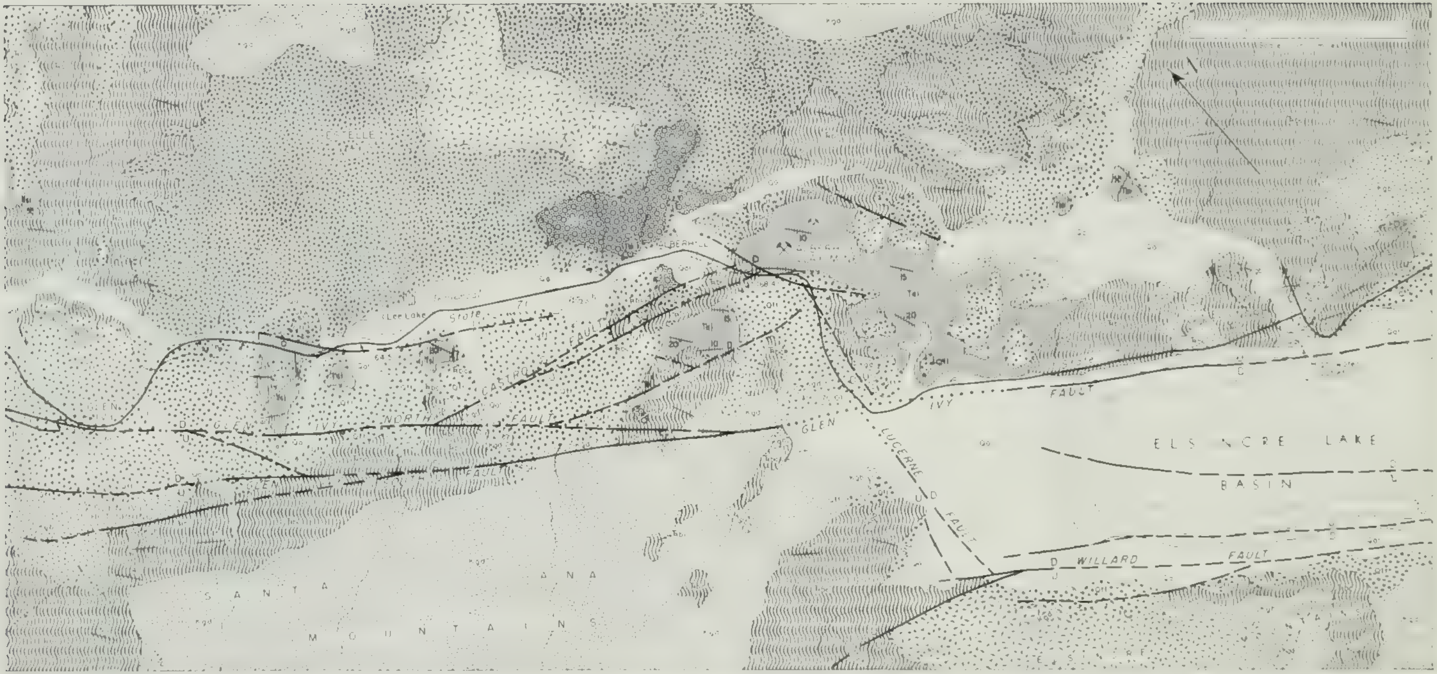
50.7 Corona, Sixth and Main Streets.

Corona to Elsinore—23.6 Miles
(Maps 4, 5; Table 2)

Santa Ana Mountains and Temescal Trough. The northwest-trending Santa Ana Mountains have a distinctly asymmetric transverse profile, and both their steep northeast face and their longer and more gently sloping southwest flank are gashed by numerous deep canyons. Most of the range is composed of igneous and metamorphic rocks, chief among which are the Bedford Canyon formation, the Santiago Peak volcanics, and several representatives of the southern California batholith (table 2). Sedimentary rocks of Upper Cretaceous to middle Miocene age dip off the lower parts of the range on its southwest side, and are preserved at progressively higher levels toward its northwest end.

In general, the foliated rocks of the older sequence appear to form a northeast- to east-dipping homocline that is interrupted in many places by masses of intrusive rocks and is otherwise very complex in detail. A broad, northerly plunging anticline is suggested by the distribution and attitude of the metasedimentary and metavolcanic rocks in the northwestern part of the range. The younger structure of these mountains, as revealed by the flanking sedimentary strata, is essentially that of a large uplifted block, tilted to the southwest and much broken by faults; the part of the range immediately southwest of Corona, however, may be gently anticlinal (Gray, 1954).

Flanking the Santa Ana Mountains on the northeast is an elongate, trough-like depression that is drained by Temescal Wash. It extends from Corona to Elsinore Lake, a distance of about 18 miles, and is in part defined by fault zones of the Elsinore system. Cenozoic sedimentary rocks and older crystalline rocks are exposed on its floor, and the much higher ground on both sides consists almost wholly of the older rocks. Parts of this narrow trough are truly graben-like, but much of it is bordered by faults on the southwest side only (Maps 4, 5); it may well owe its present topographic position as much to erosion of relatively soft sedimentary rocks as to recent block faulting.



Map 5. Glen Ivy to Elsinore. Qal—alluvium; Qft—older alluvial deposits; Tsi—Silverado formation; Kgd—granodiorite, quartz monzonite, and granite; Kt—tonalite; Kgb—gabbro and norite; Jtw—Temescal Wash quartz latite porphyry; Jsp—Santiago Peak volcanics; TRbc—Bedford Canyon formation. See Table 2 for stratigraphic relationships and descriptions of these geologic units. *Geology after Gray (1954) and Larsen (1948); modified by R. H. Jahns.*

In the area southeast of Corona the floor of the depression is about 3 miles wide, and is underlain by fault-bounded slices of folded Tertiary strata. The principal fold is a moderately tight syncline that may correspond to the Arena Blanca syncline of the Chino Hills, on the opposite side of the Chino fault (Gray, 1954). Several of the faults in this area probably extend northwestward beneath the alluvium of the San Bernardino Valley, and may define parts of the basin that lies immediately northeast of the Chino Hills.

50.7 Corona. Drive south on Main Street (State Highway 71).

52.1 Turn left (east), and continue on State Highway 71 through an area of extensive citrus groves.

54.4 The highway enters the lower part of the Temescal trough. This part of the valley is floored with alluvial-fan detritus, mainly of late Pleistocene and early Recent age. Several low mounds and ridges that project through this cover are underlain by southwest-dipping strata of the Puente formation. The low hill to the left (northeast) consists of fine-grained granodiorite porphyry.

55.3 Turn left (northeast) for side trip into Temescal Canyon.

Temescal Canyon Side Trip

(0.4) The road crosses a small creek and thence extends across a thick, dike-like body of granodiorite that is a part of the southern California batholith. This body is flanked by masses of older and somewhat finer-grained granodiorite porphyry.

(0.9) Roadcuts in deeply weathered granodiorite porphyry.

(1.2) Quarry and plant of Minnesota Mining and Manufacturing Company. The large quarry has been developed in the Temescal Wash quartz latite porphyry, a fine-grained, dark-colored intrusive rock that antedates the rocks of the southern California batholith.

Roofing granules are produced in the plant, which was erected at the site of an old quarry in 1948. The major output is fine-grained material for processed roofing; additional smaller amounts of coarse granules are produced for built-up roofing. A ceramic coating is applied to the material in a wide range of colors. The plant is the largest of its kind on the Pacific Coast, and the product is shipped to points as far distant as Vancouver, British Columbia.

Some of the very large quarry blasts in this operation have furnished valuable data for seismological and other geophysical research projects.

About 2 miles east of this point is the Cajalco mine, from which tin valued at about $60,000 was produced during the period 1890-92. The cassiterite occurs in veins and irregular masses of quartz and tourmaline that transect granodiorite of the southern California batholith. Few deposits have stimulated as much activity and have yielded as proportionately little tin as this and others in the vicinity.

Retrace route to State Highway 71.

55.3 Continue southeastward on State Highway 71.

55.5 The highway crosses a broad, low ridge that is underlain by southwest-dipping sandstone and siltstone of the Puente formation. These strata are flanked and overlapped by reddish-brown alluvial-fan deposits of Quaternary age.

56.2 To the left (northeast), on the opposite side of the canyon, is the remnant of a terrace cut on slaty rocks of the Triassic Bedford Canyon formation.

56.5 Brick yard. Alluvial deposits are worked locally as a raw material for bricks, but the principal source material for brick and tile making in this valley is clay from the Paleocene Silverado formation.

57.1 Pits and plant of Owens Illinois Glass Company. The large pits have been excavated in poorly consolidated, fine-grained arkosic sandstone and subordinate pebble conglomerate of the Silverado formation. These beds underlie a low ridge and several small hillocks, where they are capped by patches of Quaternary terrace gravels. The unconformity between the two units is well exposed on the wall of an older pit that lies immediately east of the road.

The sandstone, which contains about 40 percent of clay and silt, is washed and scrubbed in the plant on the east side of the road. Biotite, magnetite, and other iron-bearing minerals are removed magnetically. The product, a clean, high-silica sand, is used mainly in the manufacture of bottles.

58.2 Turn right (west) for side trip on Bedford Motorway.

Bedford Motorway Side Trip

(0.2) The road rises onto a low, gravel-veneered ridge that is underlain chiefly by coarsely clastic nonmarine beds of the Oligocene(?) Sespe formation.

(0.5) Terrace deposits that cap the ridge to the north have shed coarse debris over the lower slopes, on which Sespe strata are poorly exposed. Beyond this point the road crosses a thin, essentially vertical fault slice of Puente strata (Map 4).

(0.8) Forest Service gate. Proceed on foot for approximately 1 mile. Beyond the gate the Bedford Motorway and the canyon immediately southeast of it cross fault blocks of Sespe and Silverado strata, which are in part concealed by as much as 80 feet of coarse, reddish-brown gravels of late Pleistocene age. In this area the Chino and Gypsum fault zones converge southeastward to form the Glen Ivy fault zone (Map 4). The Bedford Canyon formation underlies the mountain slopes beyond the area of faulting.

Retrace route to State Highway 71.

58.2 Continue southeastward on State Highway 71.

59.1 Deadman Curve. The road skirts a projection of Quaternary gravels. The brownish, smoothly rounded hills to the left (northeast) are underlain chiefly by the Bedford Canyon formation. The pits farther east on these hills have been excavated in patches of Silverado clay and sandstone that lie upon the older crystalline rocks.

59.5 Turn right (southwest) onto Temescal Ranch road, along which a considerable thickness of reddish-brown Quaternary gravels is exposed.

60.2 Turn left (southeast) onto a gravel road and follow the trace of the Glen Ivy North fault. This active break has distinct topographic expression, and here has formed an anomalous southwest-facing scarp in Quaternary gravels; this scarp lies athwart the general direction of drainage in the area (fig. 5). To the northwest the position of the fault is marked by saddles and aligned gullies in several ridges. The trace of the Glen Ivy South fault lies at the base of the mountain front to the right (southwest).

60.7 Bear left on gravel road. The large white buildings ahead and to the right are at Glen Ivy Hot Springs, on the trace of the Glen Ivy South fault.

61.2 Turn left (northeast) and cross a canal, continuing on dirt road to rejoin State Highway 71. The road crosses a linear depression and sag pond of the Glen Ivy North fault.

61.4 Turn right (southeast) on State Highway 71.

61.7 Glen Ivy. The fault, which lies immediately southwest of the road, has some surface expression here, but its trace is partly concealed by deposits of Recent alluvium.

62.5 Santa Fe Railway underpass.

63.9 Arkosic sandstone and conglomerate of the Silverado formation are exposed beneath Quaternary gravels in several railroad cuts. The Silverado strata have been faulted against Temescal Wash quartz latite porphyry to the northeast, and the trace of the fault appears about 100 yards from the road on the left. The position of this fault to the southeast is marked by springs, clusters of trees, and dense growths of chaparral.

Temescal Wash swings around the hill northeast of the road, where it occupies a gorge cut into hard crystalline rocks. The stream appears to have been superimposed from a cover of Tertiary sedimentary rocks that once filled the valley to much higher levels (Dudley, 1936).

64.5 Lee Lake.

65.0 The road traverses an area of dissected alluvial-fan gravels, which lie upon Silverado strata and locally lap against projections of older crystalline rocks.

67.3 Alberhill. This is an area of long-time clay mining, wholly in residual and transported deposits that are parts of the Paleocene Silverado formation (Hill, 1923; Sutherland, 1935). The three main commercial products have been fire clays, refractory-bond clays, and red-burning common clays, and during recent years the annual production has amounted to about 200,000 tons.

The low hill on the far side of the railroad tracks and immediately west of the large brick and tile plant consists of Santiago Peak volcanics, the formation that was weathered to yield most of the clay in this area. The higher hills west and south of the plant are underlain by the older Bedford Canyon formation.

The large open pits southeast and southwest of Alberhill have been developed in the basal part of the Silverado section, which dips moderately southwest and rests mainly upon the Santiago Peak volcanics and genetically related intrusive rocks. The general structure of the Tertiary strata may be synclinal, but they have been much dislocated by faulting.

68.4 Alberhill clay mine. This is by far the largest mine in the district. It was worked sporadically for lignite, chiefly by underground methods, during the period 1894-1902, and much coaly material is visible on the dumps. In more recent years open-cut operations have yielded large amounts of clays from deposits whose general downward succession is as follows:

1. Yellowish, blocky clay; used mainly for sewer pipe	15-20 feet.
2. Gray to white, blocky clay, sandy in upper part and locally carbonaceous near base; used mainly for fire brick and terra cotta	26-38 feet.
3. Lignite and lignitic coal with high ash content	0-9 feet.
4. Gray high-alumina clay, locally pisolitic, generally with conchoidal fracture; non-plastic parts used in refractory wares, and plastic parts used as refractory-bond clays	4-6 feet.
5. Pinkish to reddish brown, red-burning clay, with local fragments of highly altered crystalline rocks; used mainly for brick, sewer pipe, and common tile	0-20+ feet.

The lowermost unit is in large part residual, and its downward gradation into metasedimentary rocks and quartz latite porphyry is well exposed on the north slope of the hill. The other units consist entirely of transported material. All but the uppermost of these units are illustrated in figure 6.

69.3 The hill to the left (east) is underlain by stratigraphically higher parts of the Silverado formation, chiefly arkosic sandstone with lenses of pebble conglomerate.

70.0 Summit of grade. About 0.2 mile ahead, the road crosses the Glen Ivy fault zone, which here is relatively narrow.

Elsinore-Temecula Trough. A well-defined elongate valley, known geologically as the Elsinore-Temecula trough, extends southeastward from the basin of Elsinore Lake to the Agua Tibia Mountains, a distance of about 25 miles. It is 1 to 3 miles wide, and its northwestern part is bounded on both sides by much higher ground. Structurally it is a graben within the broad Elsinore fault zone, and thus is a southeastward continuation of the Temescal trough. High-angle faults are present on both sides of the valley, and several other faults branch east-southeastward from its northeastern margin.

The central part of the trough is underlain by as much as 3,000 feet of upper Pleistocene and Recent nonmarine deposits, which rest mainly upon pre-Tertiary crystalline rocks. The structure is complicated in detail by numerous fault blocks and slices, some of which contain sedimentary rocks that may be Tertiary in age.

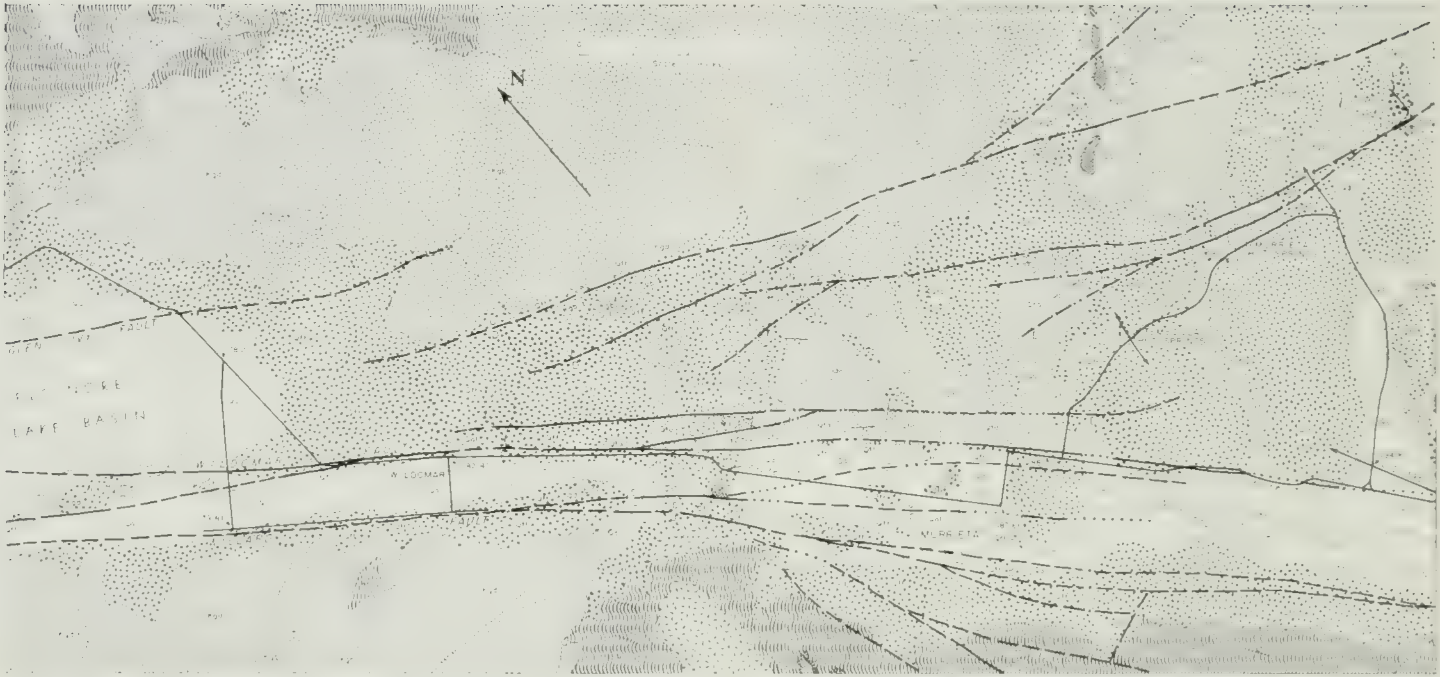
Erosional surfaces of low relief are preserved at several levels in the southeastern extension of the Santa Ana Mountains, southwest of the valley, and in the broad area known as the Perris block, northeast of the valley. The history of their development, which has not yet been deciphered to the satisfaction of all geologists familiar with the region, is intimately related to the history of the Elsinore-Temecula trough. It has been discussed by Dudley (1936), Larsen (1948, pp. 5-15), and others, and only its latest chapters need be considered here.

It seems likely that a widespread mature surface had been cut on the crystalline rocks of the region prior to mid-Pleistocene time. Its continuity was interrupted by numerous monadnocks, and older surfaces were present at higher levels. Parts of this early Pleistocene surface are preserved on the Perris block at a general altitude of 1,700 feet, and it may be represented in the southeastern extension of the Santa Ana Mountains by broad surfaces at altitudes near 2,200 feet (Larsen, 1948, pp. 10-12). The early Pleistocene San Jacinto River probably flowed southwestward across what is now the Elsinore-Temecula trough and past the southeastern end of the Elsinore Mountains to the sea. The Temecula Creek-Santa Margarita River drainage seems to have followed a somewhat similar course in areas to the southeast.

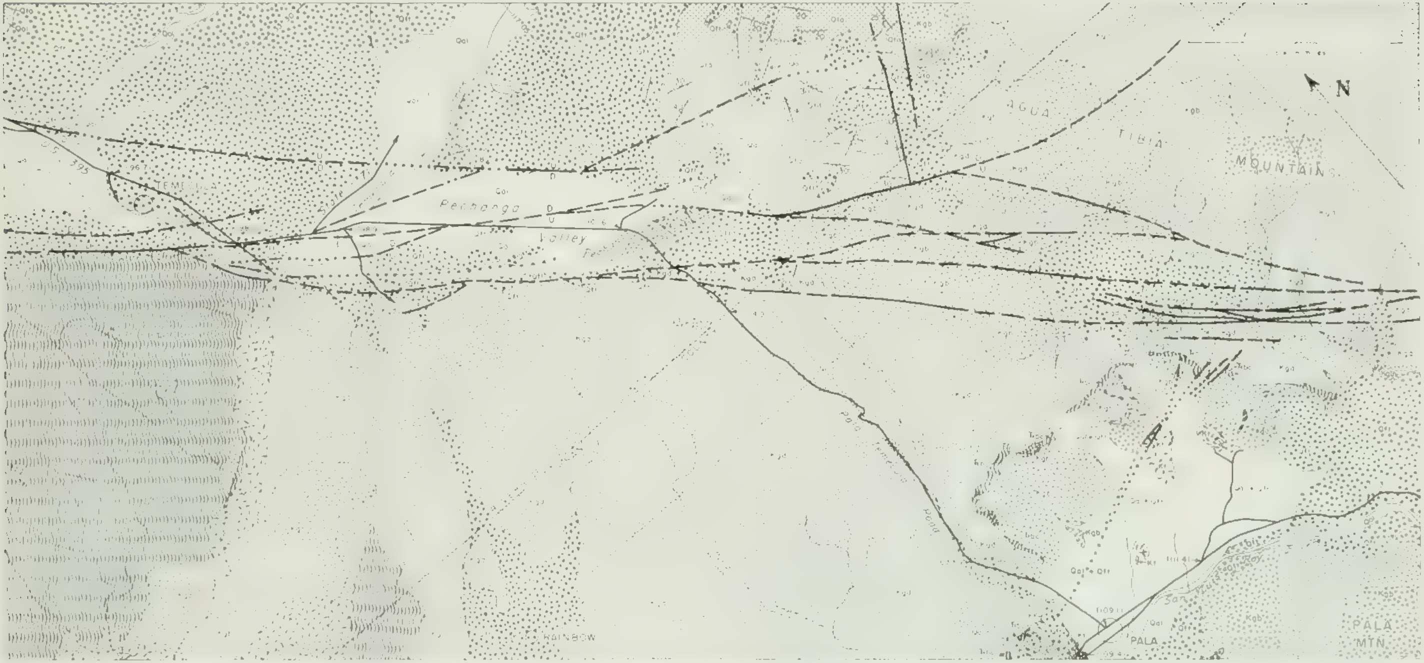
Diastrophism in middle Pleistocene time developed the Elsinore-Temecula trough along a pre-existing zone of faulting, and in effect raised the Santa Ana Mountains and the mountains to the southeast as a barrier against the general course of drainage. The Santa Margarita River evidently was able to cut downward in pace with this uplift, and developed an antecedent gorge (Temecula Canyon) through the mountains. The San Jacinto River, in contrast, was deflected along the floor of the trough, and may well have flowed southeastward to join Temecula Creek and the Santa Margarita River. Later it probably was captured by Temescal Creek to the northwest.

One or more lakes undoubtedly occupied the floor of the trough during parts of late Pleistocene and Recent time. The present basin of Elsinore Lake is a result of Recent warping and faulting, and is bounded on the southeast by a low divide. During prolonged periods of wet years the basin fills and discharges through the town of Elsinore into Temescal Creek; during drier periods the lake drops to levels well below its outlet, and it is known to have disappeared completely several times during the period of historic record.

72.3 The highway skirts the northeast side of the Elsinore Lake basin, and lies immediately above a recent fault scarp that has been modified by wave action. The fault is a part of the Glen Ivy zone. The hill on the left (northeast) is underlain by schistose rocks and quartzite of the Bedford Canyon formation.



Map 6. Elsinore to Murrieta Hot Springs and Temecula. Qal—alluvium; Qft—older alluvial deposits; Qta—Temecula arkose; TQb—basalt; TQa—older arkose; Kgd—granodiorite, quartz monzonite, and granite; Kt—tonalite; Kgb—gabbro and norite; Ꞅbc—Bedford Canyon formation. See Table 2 for stratigraphic relationships and descriptions of these geologic units. *Geology after Larsen (1948) and Mann (1951); modified by R. H. Jahns.*



Map 7. Temecula to Pala. Qal—alluvium; Qft—older alluvial deposits; Qta—Temecula arkose; Kgd—granodiorite, quartz monzonite, and granite; Kt—tonalite; Kgb—gabbro and norite; Ꞧbc—Bedford Canyon formation. See Table 2 for stratigraphic relationships and descriptions of these geologic units. *Geology by R. H. Jahns.*

On the opposite side of the lake is the Willard fault zone. This zone, together with the Glen Ivy zone and the north-trending Lucerne fault, outlines the northwest end of the Elsinore-Murrieta graben (Map 5).

74.2 The road crosses the surface outlet of Elsinore Lake.

74.3 Elsinore, Graham Avenue and Main Street.

Elsinore to Pala—34.8 Miles
(Maps 5, 6, 7; Table 2)

74.3 Turn right (southwest) onto Main Street.

74.7 Rome Hill, an uplifted slice of Pleistocene fanglomerate between the Wildomar and Willard faults, rises from the lake plain on the opposite side of the basin.

76.2 Bridge over San Jacinto River.

76.8 Plutonic rocks of the southern California batholith (Cretaceous) form the hills to the left (east-northeast). Coarse-grained granodiorite yields light-colored, bouldery exposures, whereas gabbroic rocks weather to brownish slopes on the lower hills farther east.

In the area between here and Perris, 10 miles to the north, are numerous small gold mines and prospects. The mineralization is in quartz veins, most of which cut tonalite and other batholith rocks. A few others are in the older metamorphic rocks. Production from the area has amounted to about $2.5 million, mainly in gold and some silver (Sampson, 1935).

78.2 Bear right (southwest) onto a paved road, and cross the lake plain.

79.2 The road crosses the small trench of a fault that extends along the base of a low, elongate ridge of upper Pleistocene alluvial-fan gravels. To the left (southeast), a similar upraised mass lies on the opposite side of the same active fault. The road crosses a second fault about 0.2 mile beyond this point.

These and other faults in the valley are effective ground-water barriers, and several of them separate blocks of ground in which the water levels are known to differ by 200 feet or more.

79.8 Turn left (southeast) on a paved road.

80.1 To the left (northeast and east) is a distinct southwest-facing scarp on the valley floor. It marks the trace of the Wildomar fault. The Willard fault zone trends parallel with the road at the right and only a few hundred feet away. Much of its trace is buried beneath modern alluvium; but several anomalous cols and knobs on the low ridges probably are surface expressions of the fault zone. These are present for a strike distance of more than a mile.

81.9 Turn left (northeast) on the road to Wildomar.

82.4 Wildomar. Turn right (southeast) onto State Highway 71.

83.6 The hills immediately adjacent to the highway on the left consist of arkosic sandstone and siltstone of the Pleistocene Temecula arkose (Mann, 1951). This formation constitutes the oldest known part of the exposed sedimentary fill in the Elsinore-Temecula trough, and is overlain by younger and less deformed fluviatile deposits that also are Pleistocene in age. These are exposed in the dissected valley-bottom area to the right (southwest).

84.9 The road jogs to the right around a spur of highly deformed sandstone and conglomerate that are younger than the Temecula arkose. The steep dips of the beds probably are the result of drag along several subparallel breaks in the Wildomar fault zone. The Willard fault zone is only about a quarter of a mile to the right (southwest) in this area, and its position probably is marked by a Quaternary dike of nepheline basalt that crops out along Murrieta Creek. The deepest part of the graben thus is very narrow here, but it widens considerably to the southeast.

The mountain spur on the opposite side of the valley consists of tonalite, whose light-colored, bouldery outcrops are in marked contrast to the brownish, smoothly sculptured slopes underlain by the Bedford Canyon formation farther southeast. About 4 miles due south is Mesa de Burro, a remnant of an old erosion surface that is capped by olivine basalt of late Tertiary or Quaternary age.

85.2 The small quarry about 0.2 mile to the left (northeast) exposes a bed of white rhyolite tuff, which is underlain by bluish clay and overlain by sandstone and fine-grained siltstone. The section dips about 35° southwest, and occupies a narrow fault block. It might be of Miocene age, as suggested by Larsen (1948, p. 107), but more likely it is a part of the Temecula arkose.

87.4 Murrieta. Several wells in this part of the valley provide data that not only establish the positions of at least six subparallel faults within a strip about a mile wide, but plainly indicate the graben-like structure beneath the valley floor. As much as 2,500 feet of the Temecula arkose is present in the deepest block, where it is overlain by 300 to 500 feet of younger Pleistocene deposits (fig. 7). The olivine basalt of

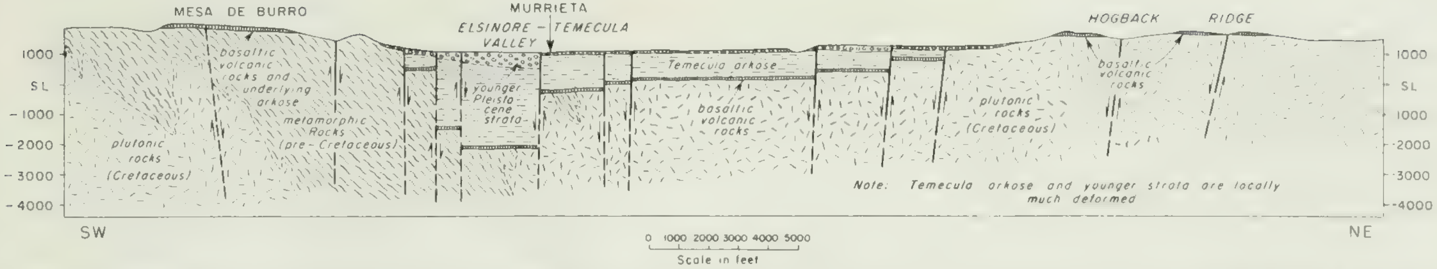

MESA DE BURRO
MURRIETA
ELSINORE – TEMECULA VALLEY
HOGBACK RIDGE
1000
SL
– 1000
– 2000
– 3000
– 4000
basaltic volcanic rocks and underlying arkose
metamorphic Rocks (pre-Cretaceous)
plutonic rocks (Cretaceous)
younger Pleistocene strata
Temecula arkose
basaltic volcanic rocks
plutonic rocks (Cretaceous)
basaltic volcanic rocks
Note: Temecula arkose and younger strata are locally much deformed
1000
SL
1000
-2000
-3000
-4000
SW
NE
0 1000 2000 3000 4000 5000
Scale in feet

FIGURE 7. Cross-section through the Murrieta area from Mesa de Burro to Hogback Ridge, showing the general structure of the Murrieta graben. This is a local feature of the Elsinore fault zone, and dates from early or middle Pleistocene time. *Based in part upon data from Larsen (1948) and Mann (1951).*

Mesa de Burro is an excellent index of the vertical components of displacement in the faulted area, as it has been penetrated in the subsurface and also crops out on Hogback Ridge, about 3½ miles northeast of Murrieta (fig. 7). The maximum vertical offset indicated by this basalt is about 4,000 feet.

87.6 Turn left (northeast) at corner.

88.2 Turn right (southeast) at corner.

88.7 Turn left (northeast) onto Murrieta Hot Springs road, which traverses gently rolling country underlain by upper Pleistocene valley fill (Map 6).

89.9 Cross U. S. Highway 395.

90.5 Temecula Hot Springs. The springs mark the trace of a fault that extends eastward from the vicinity of Murrieta.

91.2 Murrieta Hot Springs. A group of subparallel, east-trending faults extends through this area, and separates strata of the Temecula arkose from gabbroic rocks of the southern California batholith on the north. The trace of the main break lies immediately beyond the large cluster of buildings.

92.4 Turn right (south) onto Winchester Road.

94.8 Turn left (southeast) onto U. S. Highway 395, which crosses the trace of the Wildomar fault at a very acute angle.

95.5 The southeast-facing scarp of the Wildomar fault is at the left, and the trace of the fault is marked by several springs that contribute water to the swampy ground crossed by the highway.

96.7 Roadcut exposures of typical upper Pleistocene valley fill, chiefly arkosic sandstone and pebble conglomerate that are locally cross-bedded (fig. 8). This poorly consolidated material is a part of the Pauba formation of Mann (1951), and is younger than the Temecula arkose.

96.8 Temecula lies to the right (southwest).

97.9 About half a mile ahead and to the right (south) is the slot-like upper end of Temecula Canyon, through which the antecedent Temecula Creek-Santa Margarita River drainage crosses the mountains that adjoin the Elsinore-Temecula Valley. This rugged defile has been the scene of several spectacu-

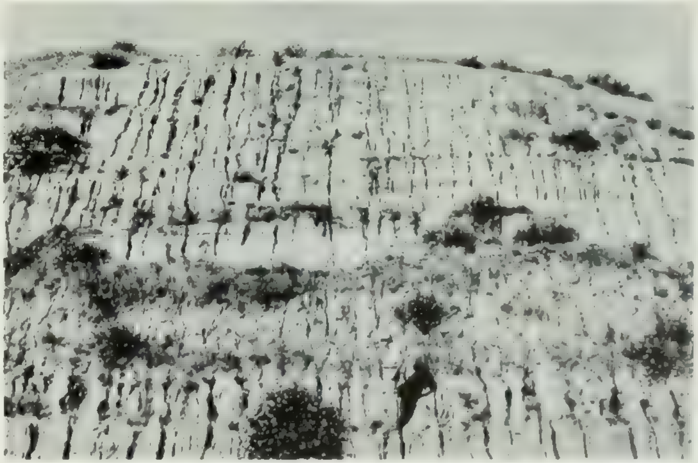


FIGURE 8. Roadcut exposure of poorly consolidated arkosic sandstone and pebble conglomerate near Temecula. This valley fill is late Pleistocene in age, and is a part of the Pauba formation of Mann (1951).

lar floods during historic times. In 1884, for example, the original San Diego line of the Santa Fe Railway, which had been built through the canyon only two years earlier, was obliterated by flood waters that in places were more than 25 feet deep; many of the ties and bridge timbers were encountered by ships 100 miles out at sea. After much of the line was again washed out a few years later, it was abandoned in favor of a more practical route along the coast.

The brownish hills northwest of the canyon are underlain by schists and quartzite of the Bedford Canyon formation, and those to the southeast by coarse-grained granodiorite of the southern California batholith.

98.0 Turn left (southeast) onto State Highway 71.

98.1 The Agua Tibia Mountains lie directly ahead.

Agua Tibia Mountains. The Agua Tibia Mountains, which rise to heights of slightly more than 6,000 feet, are approximately 20 miles long and 8 miles in average width. Their southeastern end slopes into the Warner Basin, and their northwestern end is separated from the Elsinore-Temecula Valley by a foothills area of complex block faulting. This rugged and bold-faced range is essentially an uplifted block of pre-Tertiary crystalline rocks that is bounded on the southwest by the Elsinore fault zone and on the northeast by the Aguanga fault zone. These zones converge northwestward, and merge to from the Elsinore fault system in the areas beyond Murrieta.

The range is composed of plutonic rocks (chiefly tonalites), older metamorphic rocks that probably are in part correlative with the Bedford Canyon formation of the Santa Ana Mountains, and a wide variety of injection gneisses and other hybrid rocks. At least three large faults are known to cut these rocks within the main mountain block, and a cover of Pleistocene sedimentary rocks is preserved in several depressed fault blocks at the northwest end of the range.

98.7 Bear right onto Temecula Road.

98.9 Bridge over Temecula Creek; bear left onto Pala-Temecula Road immediately beyond.

99.2 The road traverses the smooth floor of Pechanga Valley, which is flanked by dissected low benches of upper Pleistocene fluviatile deposits. The low scarp on the northeast side of the valley is associated with one of the principal faults of the Elsinore zone; this same fault extends through the prominent saddle in the skyline ridge directly ahead. The rolling hills between the valley floor and the main slope of the mountains to the east and southeast are underlain chiefly by the Temecula arkose.

101.6 Turn left (northeast) onto a paved road that extends up the valley of Pechanga Creek.

102.1 A small knob of Temecula arkose lies to the right (south), at the far side of the creek. The beds dip steeply southwest, and probably have been dragged along one of the breaks in the Elsinore fault zone. The arkose consists chiefly of quartz, muscovite, and essentially fresh feldspars and biotite, together with small pebbles of granodiorite. Analyses indicate that, within the limits of sampling error, its bulk mineralogical and chemical composition is the same as that of the granodiorite exposed on nearby hills. Evidently the sediments were derived mainly from disintegrated granodiorite, were not transported far, and were laid down rapidly under conditions that permitted little chemical weathering.

Retrace the route to Pala-Temecula Road.

102.6 Turn left (southeast) onto Pala-Temecula Road.

103.3 Some of the low, rolling hills in this area are underlain by upper Pleistocene arkose, and others by granodiorite. It is very difficult to distinguish the two rocks in areas of weathered exposures.

FIGURE 9. The Mission Asistencia at Pala, as it appeared shortly after the turn of the present century. *Photo courtesy of Mrs. Frank A. Salmons.*

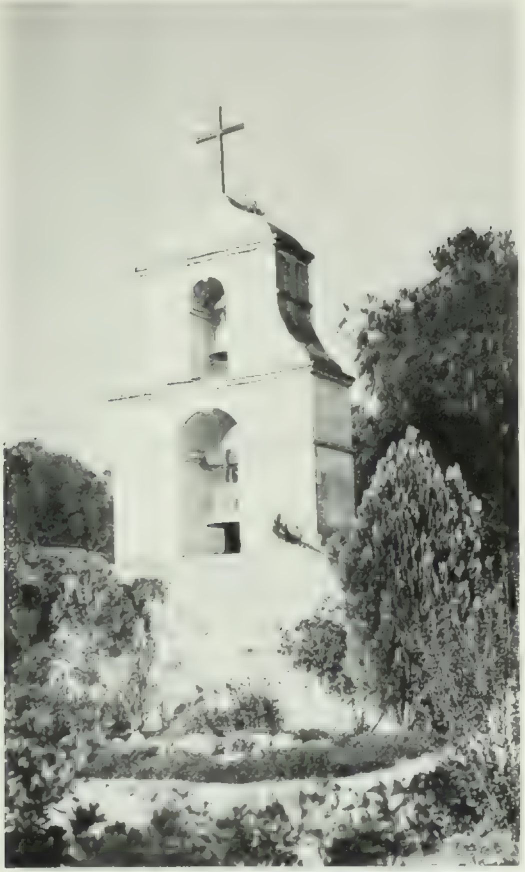


FIGURE 10. The detached bell tower of the reconstructed Pala mission, as it appears today.

104.0 Riverside-San Diego county line.

104.1 Summit. This pass is only about 250 feet above Temecula Creek 4 miles to the northwest, but is more than 900 feet above the San Luis Rey River, which is an equal distance to the south. Pala Creek, a south-flowing tributary of the San Luis Rey River, has carved a deep canyon and is working briskly headward at the present time; it seems likely that it will capture Temecula Creek and the drainage of much of the Elsinore-Temecula Valley within a short period of geologic time.

104.8 Roadside outcrop of Woodson Mountain granodiorite, one of the principal rock types in the southern California batholith. The coarse-grained rock here exposed contains an unusually large number of inclusions, but otherwise is typical for this area.

105.5 Pala Canyon is at the left (east).

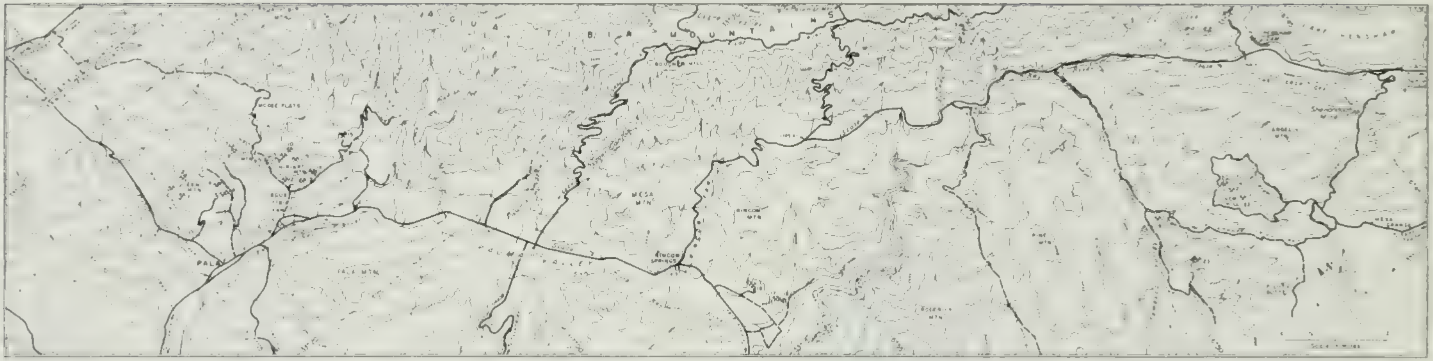
105.9 Numerous roadcut exposures of Woodson Mountain granodiorite with well-developed planar structure that is emphasized by weathering. The structure is thought to be a result of primary flowage during intrusion. The same rock is well exposed on the opposite side of the canyon, where its outcrops are markedly different in appearance from those of the gabbro and norite on the upper slopes of Queen Mountain to the south. The granodiorite is separated from the gabbroic rocks by a screen of quartzite, schist, and fine-grained granodiorite that probably is in part of metasomatic origin.

The old dumps and two small buildings below and to the right of the summit of Queen Mountain mark the position of the Tourmaline King mine, one of the gem mines of the Pala district.

107.5 Cross Pala Creek.

108.2 The road crosses the alluvial floor of the San Luis Rey River Valley. Pala Mountain, a large mass of gabbroic rocks, lies ahead; the cliff-faced mountain ahead and to the right (southwest) consists mainly of leucogranodiorite.

109.1 Pala. The outstanding feature of this small Indian settlement is its mission, which is on the east side of the plaza. Founded in 1815 as an assistencia, or branch, of Mission San Luis Rey, it was allowed to deteriorate in later years (fig. 9) and was further damaged by a flood in 1916. It was subsequently restored in full (fig. 10), and still remains in service. It is the only one of California's mission establishments with a detached bell tower.



Map 8. Pala to Warner Basin and Mesa Grande. Numbered mines and quarries are as follows: (1) Tourmaline King—tourmaline, quartz. (2) Tourmaline Queen—tourmaline, quartz. (3) White Cloud—tourmaline, quartz. (4) Gem Star—tourmaline, quartz. (5) Stewart—lepidolite, amblygonite, tourmaline. (6) Douglass—tourmaline, quartz. (7) Ocean View—beryl, quartz. (8) Pala Chief—spodumene, tourmaline, beryl, quartz. (9) Senpe—beryl, lepidolite, quartz, tourmaline. (10) San Pedro—beryl, spodumene, quartz, tourmaline. (11) Vanderburg—spodumene, beryl, quartz, tourmaline. (12) Katerina—spodumene, lepidolite, quartz, beryl, tourmaline. (13) Fargo—tourmaline, quartz. (14) El Molino—beryl, quartz. (15) Johnson (McGee)—dimension stone. (16) Mack—beryl. (17) Victor—beryl, tourmaline, spodumene, garnet. (18) Clark—quartz, beryl. (19) Esmeralda—tourmaline, beryl, quartz. (20) Himalaya—tourmaline, beryl, quartz. (21) San Diego—tourmaline, quartz. (22) Mesa Grande—tourmaline, beryl, quartz. (23) Rose Quartz—quartz, garnet.

Pala to Warner Springs—40.8 Miles
(Maps 7, 8, 9; Table 2)

Pala Pegmatite District. The Pala district has been a widely known source of gem and lithium minerals, and its total recorded mineral output is valued at nearly $800,000. Formal mining operations began in the eighteen-nineties, and activities were greatest during the period 1900-1914. Lepidolite, tourmaline, and gem spodumene have been the chief products, and small amounts of amblygonite, beryl, feldspar, and quartz also have been mined. The district has been studied and described by several investigators, and the reader is referred to the papers and reports of Waring (1905), Kunz (1905), Merrill (1914), Schaller (1925), Donnelly (1936), and Jahns and Wright (1951) for more detailed treatment of its geology and pegmatite deposits than appears in the following paragraphs.

The district has an area of about 13 square miles, and includes several small mountain masses on both sides of the San Luis Rey River. It is immediately southwest of Agua Tibia Mountain, and is separated from it by a broad topographic bench that marks the trace of the Elsinore fault zone (fig. 11). The district is underlain chiefly by granodiorite, tonalite, gabbro, and norite of the southern California batholith, and in some places by older metamorphic rocks. At least 400 bodies of granitic pegmatite are exposed within its borders.

Most of the pegmatite occurs as tabular masses that trend north to north-northwest and dip gently to moderately westward. They are remarkably persistent, with strike lengths of as much as a mile, and they range from thin stringers to large dikes with bulges nearly 100 feet thick. In several places they occur as swarms of closely spaced, subparallel dikes (figs. 11, 12). The dikes in some swarms branch and converge along their strike, and locally they form thick composite bodies in which each member dike retains its identity (fig. 14).

The pegmatites are most abundant in the gabbroic rocks, which are known collectively as the San Marcos gabbro (Miller, 1937; Larsen, 1948, pp. 41-53), and they appear to have been emplaced along a single well-developed set of fractures. These fractures are independent of the primary structural features of the enclosing rocks, and they transect contacts between major rock units; they may well have been subhorizontal at the time of pegmatite emplacement, and probably were developed as contraction features while the rocks of the southern California batholith were cooling on a regional scale.

Some of the pegmatite bodies are essentially homogeneous in mineralogy and texture, but most are composed of units that differ from one another in lithology. Graphic granite is

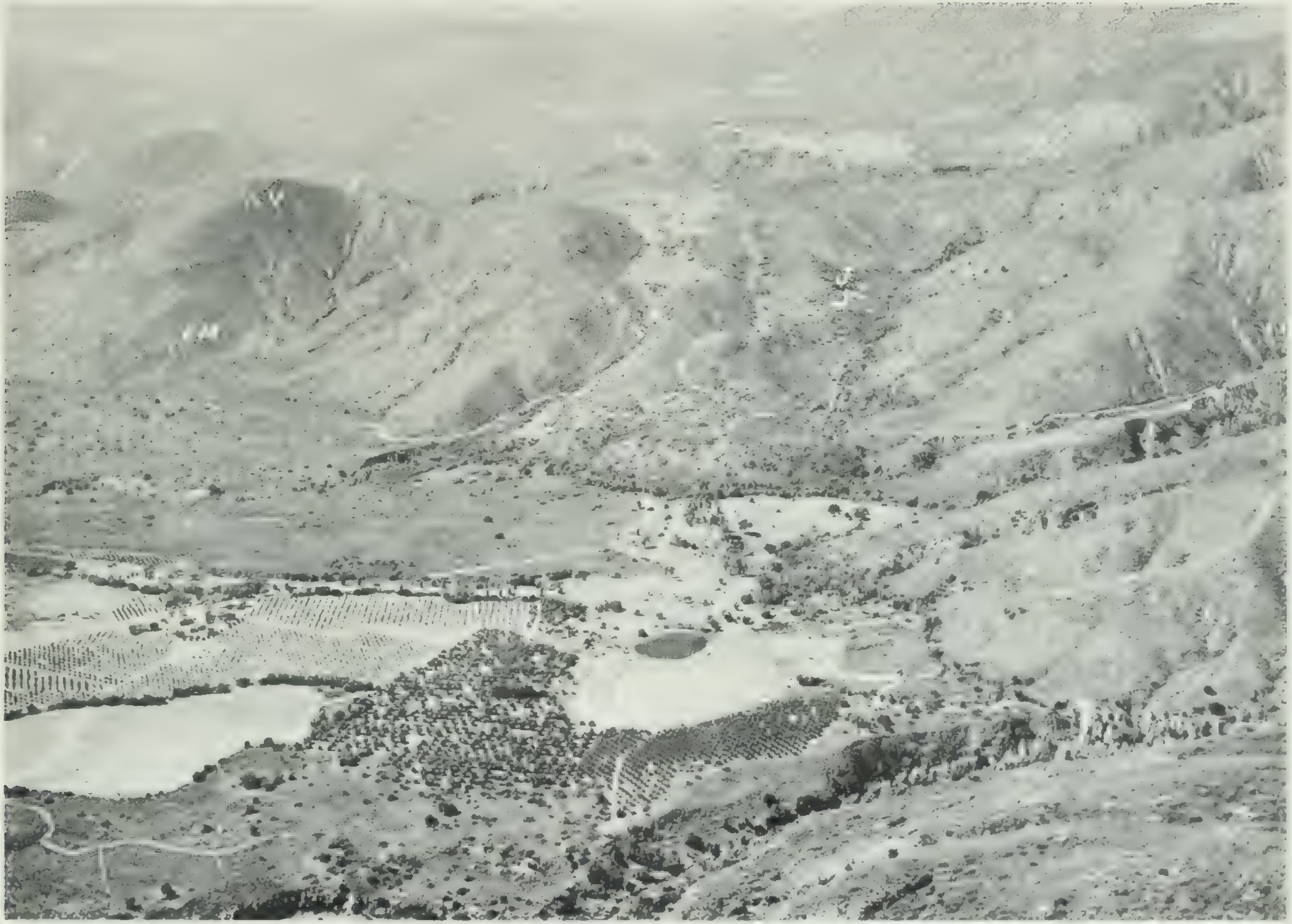


FIGURE 11. Aerial view northwestward across a part of the Pala district. The apical part of the Agua Tibia fan is in the foreground, the spurs of the Agua Tibia Mountains are at the right, and the Pechanga Valley is in the distance. The broad bench in the middle distance marks the trace of the Elsinore fault zone, here nearly a mile in width. The brecciated and sheared rocks within this zone are well exposed in Castro Canyon (CC). Numerous subparallel dikes of pegmatite form rib-like outcrops on the brushy slopes of Hiriart Mountain, at the left beyond the Agua Tibia fan. Note the contrast between the smooth slopes that are underlain by gabbroic rocks and the light-colored, bouldery slopes underlain by granodiorite; contacts between these rock types are indicated in several places by arrows. Mines visible in this view include El Molino beryl mine (EM), the Vanderburg gem spodumene mine (V), and Johnson (McGee) "black granite" quarry (J). *Pacific Air Industries photo.*

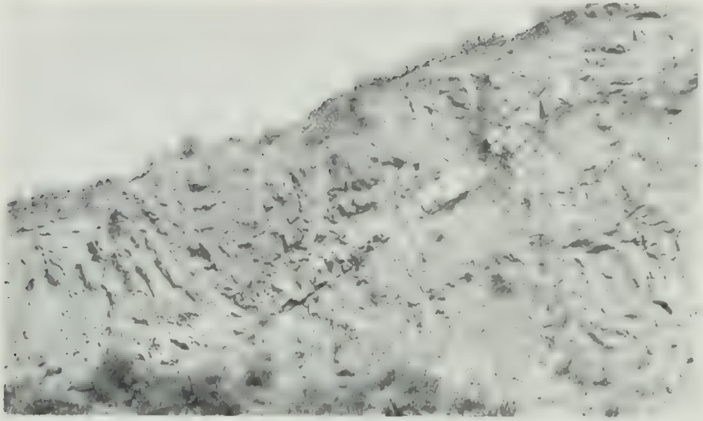


Figure 12. Dike and parallel strings of fine- to medium-grained pegmatite in Bonsall tonalite, small quarry west of Pala. The dike, about 2 feet in average thickness, comprises a hanging-wall layer of graphic granite and a footwall layer of fine-grained, aplitic rock.

the chief constituent of the outermost units, or border zones, which generally are thin, discontinuous, and fine grained. It also composes most of the adjacent, coarse-grained wall zones, which ordinarily are the thickest and most persistent of the pegmatite units (fig. 13). In general, it is more abundant in the hanging-wall parts of the larger dikes than in their footwall parts, and it constitutes nearly the full thickness of many smaller dikes.

Discoidal to highly irregular masses of coarse- and very coarse-grained pegmatite form the innermost zones, or cores, of many dikes. Some are composed of quartz, perthite, or an aggregate of these minerals, and others consist of quartz and giant crystals of spodumene. Spodumene of gem quality occurs wholly within the cores, and represents the relatively small amount of this mineral that has escaped hydrothermal alteration (fig. 15). Some of the cores are separated from nearby wall zones by one or more intermediate zones, which form discontinuous or complete envelopes around them (fig. 13). These units are present mainly in the largest dikes, and generally are rich in coarse-grained perthite.

Fracture-filling units are widespread, and consist chiefly of quartz, albite, fine-grained muscovite, or combinations of these minerals (fig. 15). Fracture-controlled replacement bodies are superimposed upon the zonal pattern of nearly all the pegmatites. They are composed mainly of albite, quartz, and muscovite, and, less commonly, of lepidolite and tourmaline. Similar mineral aggregates occur in the central parts of many dikes, where they generally appear to have corroded the surrounding pegmatite zone or zones. These centrally dis-

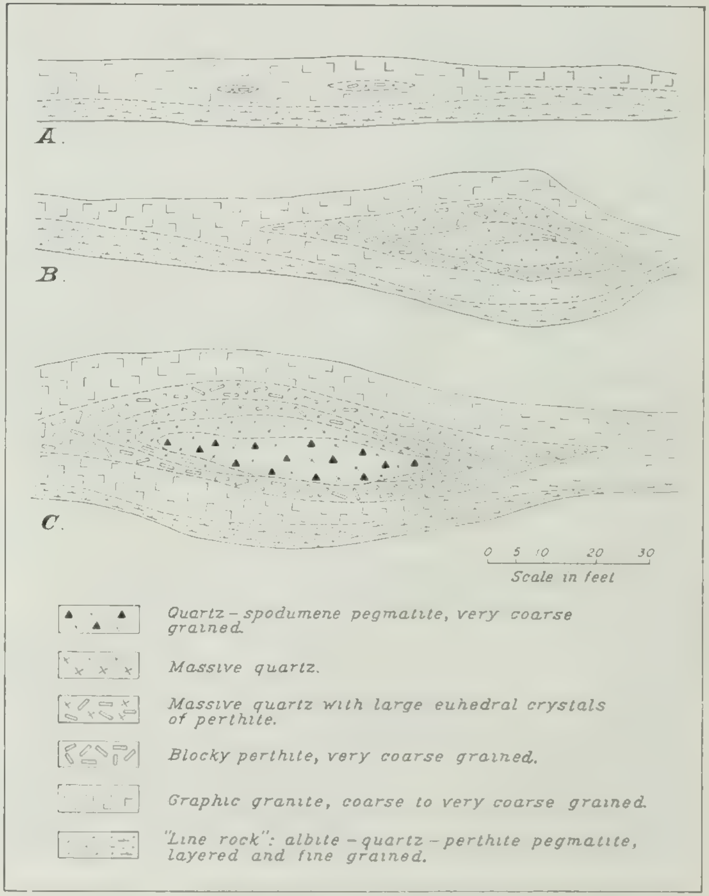

A.
B.
C.
0 5 10 20 30
Scale in feet
Quartz – spodumene pegmatite, very coarse grained.
Massive quartz.
Massive quartz with large euhedral crystals of perthite.
Blocky perthite, very coarse grained.
Graphic granite, coarse to very coarse grained.
"Line rock": albite – quartz – perthite pegmatite, layered and fine grained.

Figure 13. Idealized sections of pegmatite dikes in the Pala district, showing typical zonal structure. A. Simply zoned dike with fine-grained lower part (Tourmaline King, Tourmaline Queen). B. Bulging dike with more numerous inner zones (Ocean View, El Molino). C. Bulging dike with complex zonal structure (Stewart, Vanderburg-Katerina).

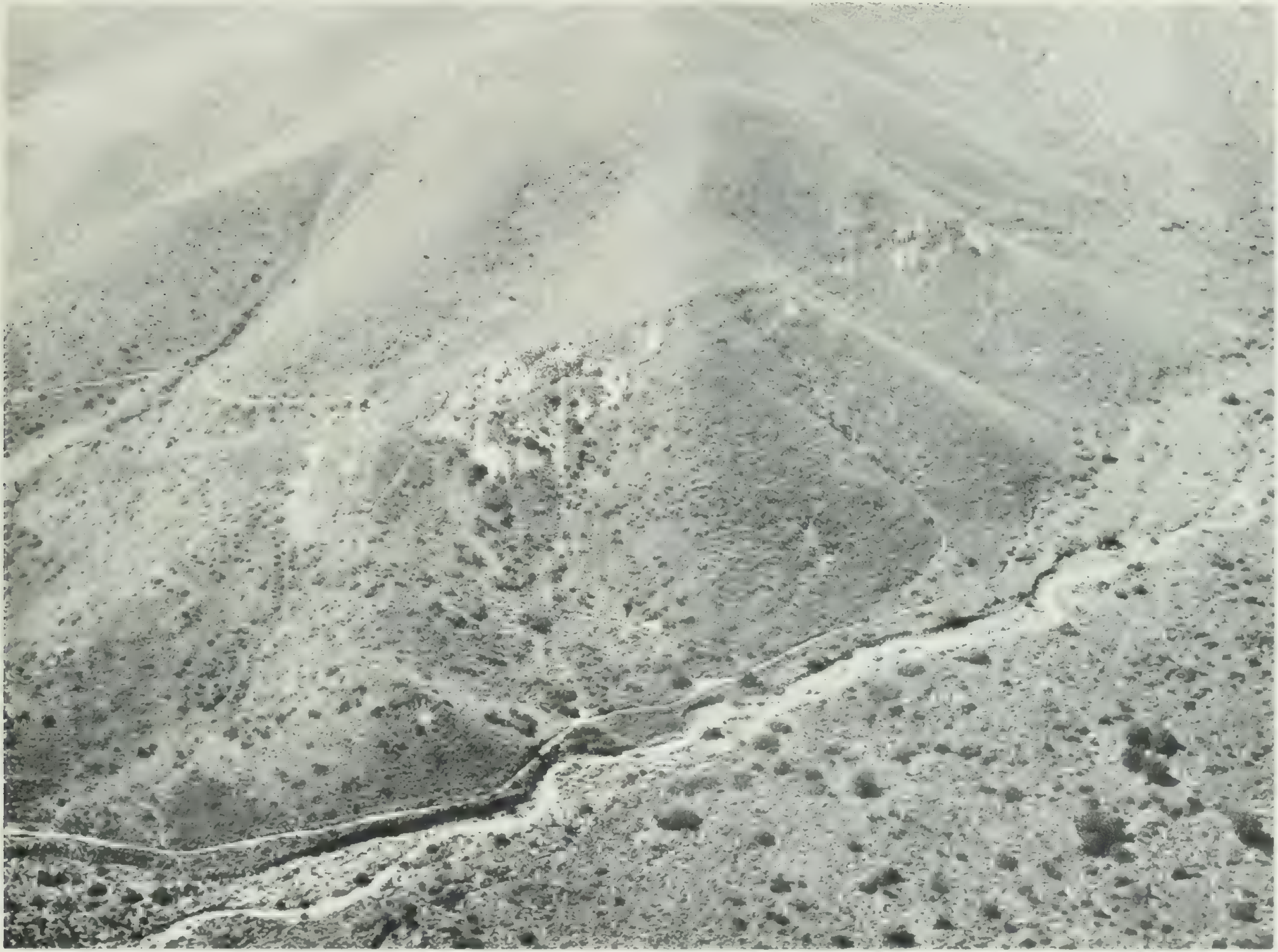


FIGURE 14. Northwestward aerial view of a part of Queen Mountain, Pala district, showing open cuts of the Stewart lepidolite mine. These workings are in the thick and bulbous southern end of a pegmatite dike that dips away from the observer, and they lead to tunnels and stopes that underlie much of the hill slope beyond the crest of the foreground ridge. The dike splits northward into two or more juxtaposed dikes whose outcrops are visible on the brush-covered slopes. Workings of the Gem Star mine appear below the cliffs in the right-hand part of the view. *Pacific Air Industries photo.*

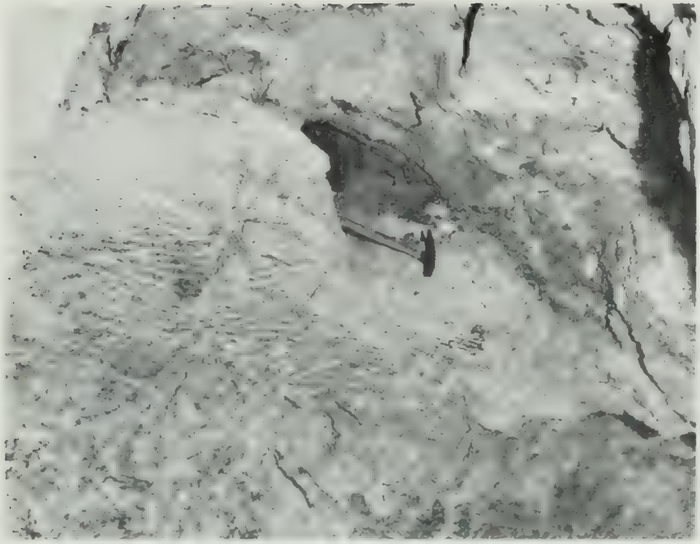


FIGURE 15. Fracture-controlled replacement masses and small fracture fillings of albite (light) in very coarse-grained quartz (dark), Pala Chief mine, Pala district. Above this striped rock is a layer of "pocket pegmatite" that has been worked for gem spodumene, and exposed in the back of the small stope is coarse-grained perthite-quartz pegmatite. Below the striped rock is albite-quartz-perthite pegmatite with subordinate muscovite and schorl.

posed units, which commonly contain residual masses of earlier minerals, include much of the district's so-called "pocket pegmatite," a rock type composed mainly of fine- to coarse-grained, subhedral to euhedral quartz, albite, potash feldspar, muscovite, lepidolite, and tourmaline.

All of the gem tourmaline, beryl, and quartz, as well as the commercial concentrations of lepidolite and much of the gem spodumene, occur in the pocket pegmatite. Very little open space is present in this type of rock, and the few large cavities that do occur are partly or completely filled with a clay through which gem crystals are scattered. The pocket pegmatite is largely restricted to cores and immediately adjacent zones, and is found chiefly along the footwalls or in the footwall parts of the cores.

Fine-grained granitoid rocks, composed mainly of quartz and albite, are common in the footwall parts of many dikes (fig. 13), and also occur elsewhere in some dikes. Several varieties are essentially uniform in texture and structure. Others, known collectively as "line rock," are strikingly marked by alternating thin layers of garnet-rich and garnet-poor pegmatite, or of schorl-rich and schorl-poor pegmatite. Layering in some of these rocks also is caused by distinct variations in texture.

The Pala pegmatite bodies are thought to have been formed by crystallization of liquid that was injected along fractures during the final stages of consolidation of the southern California batholith. The pegmatite zones appear to have developed from the walls of the bodies inward, probably by fractional crystallization and incomplete reaction with the residual liquid. Many, if not all, if the relations in the central parts of the most complex pegmatites seem best explained in terms of progressive accumulation and late-stage crystallization of mineralizing fluids, with accompanying deuteric replacement of earlier-formed minerals (Jahns and Wright, 1951, pp. 44-45). In order to develop a few of the larger replacement bodies, material may have been derived from other parts of the dikes. The origin of the line rock and other fine-grained parts of the dikes is less clear. They appear to have formed in part by replacement of earlier graphic granite, as first pointed out by Schaller (1925), but they are older than many stringers, lenses, and pods of graphic granite that occur within them.

Approximately 75 minerals are known from the pegmatites of the Pala district, and most of them still can be collected by persons with patience and a practiced eye. Indeed, the district has long been a happy hunting ground for mineral collectors. Visitors should be cautious, however, in entering the old mines, as many of them are in poor or dangerous condition. The underground workings of the Stewart and Tourmaline Queen mines (Map 8) are badly caved, and should be avoided entirely. None of the deposits should be visited without the knowledge and consent of the owners, who have suffered in the past from the thoughtless actions of some collectors.

109.1 Leave Pala, traveling west from the plaza.

109.4 Bridge over Pala Creek. Immediately beyond this bridge, a small quarry exposes a pegmatite dike and several parallel pegmatite-aplite stringers that transect medium-grained tonalite (fig. 12). This is the Bonsall tonalite, one of the most extensive rock types in the Peninsular Range province (Hurlbut, 1935; Larsen, 1948, pp. 58-67). It is younger than the gabbroic rocks and older than the granodiorites of the southern California batholith, and contains numerous mafic streaks and ovoid inclusions of partly digested gabbro, quartzite, and schist. A nearly vertical dike of aplite is exposed near the east end of the quarry.

109.7 Turn sharply left (east) onto Pala Road (State Highway 76).

110.6 Dumps of the Stewart mine are visible on the lower slopes of Queen Mountain to the left (north). This and other mines on Queen and Chief Mountains can be reached from Pala over trails and unimproved roads, as shown on Map 8.

110.8 Junction with old road into Pala.

111.4 Bear left onto paved road for side trip to Hiriart Mountain.

Hiriart Mountain Side Trip

(0.35) Turn left (northeast) onto narrow paved road.

(0.7) The broad surface of the late Pleistocene Agua Tibia fan lies to the right (southeast). Ahead is Hiriart Mountain, a mass of gabbro and tonalite whose slopes are ribbed by the outcrops of numerous pegmatite dikes.

(1.0) Bear left on McGee Road. The road on the right leads to the headquarters of George Ashley, mineral dealer and owner of several mines on Hiriart Mountain.

(1.2) Workings of the Katerina (Ashley) mine are on the hillside at the right (east). This mine has been developed in a thick and very continuous series of juxtaposed pegmatite dikes, which contain examples of all types of pegmatite found in the district. The first known occurrence of the gem spodumene kunzite was discovered on this property, which has been worked intermittently since 1902. Substantial quantities of lepidolite and gem spodumene, quartz, and beryl have been recovered from the mining operations.

Retrace route to State Highway 76.

111.4 Continue eastward on State Highway 76.

111.5 Numerous roadcuts beyond this point expose extremely coarse-grained detritus that constitutes much of the large Agua Tibia fan (figs. 11, 16). Termed the Pala conglomerate by Ellis (Ellis and Lee, 1919, p. 70), these fan deposits were derived principally from Agua Tibia Mountain and other high areas to the north. Most prominent among them are bouldery layers, some as much as 35 feet thick, that show little sorting or bedding and evidently represent old debris flows. Extensively fractured granodiorite within and near the Elsinore fault zone probably was a major source of the detritus. The deposits contain scattered vertebrate remains of late Pleistocene age, and probably are in part correlative with the younger arkosic fill of the Elsinore-Temecula trough.

113.1 Surface of the Agua Tibia fan. This point provides an excellent general view of the Pala district, and especially of the pegmatite dikes that crop out on the east sides of Queen, Little Chief, and Hiriart Mountains (Map 8, figs. 11, 14). Several boundaries between masses of gabbro and norite and younger plutons of granodiorite are clearly shown by differences in surface expression of these rocks (fig. 11). In this area most of the gabbroic plutons contain numerous pegmatite dikes, but a few appear to be pegmatite-free.

The mass of fine- to medium-grained hornblende norite on Slice Mountain, about 1½ miles to the north-northeast (fig. 11), has been quarried for dimension stone (Hoppin and Norman, 1950). This so-called "black granite," which is used mainly for monuments, is obtained from large boulders of fresh rock that are surrounded by thoroughly weathered material. Some of the residual boulders are parts of a surface layer of creep debris, whereas others have not been moved from the positions they occupied prior to weathering of the rock (fig. 17).

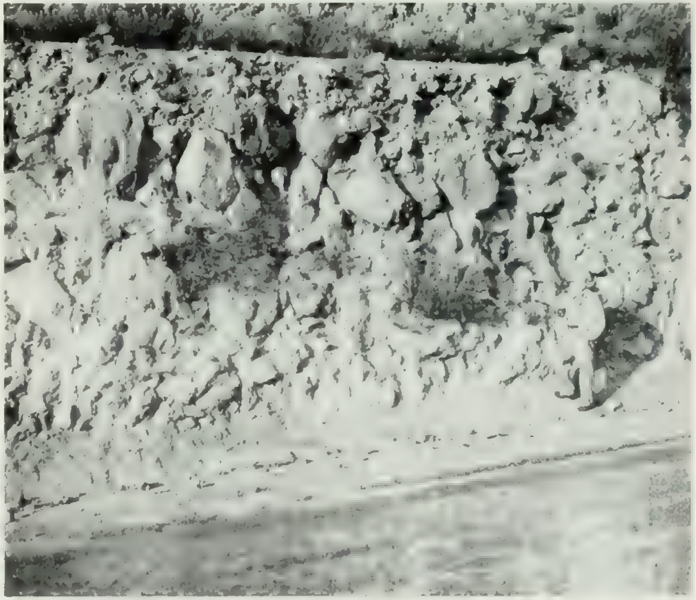


FIGURE 16. Roadcut exposure of the chaotic debris-flow deposits that constitute much of the Agua Tibia fan, Pala district. Nearly all of the fragments are Woodson Mountain granodiorite.

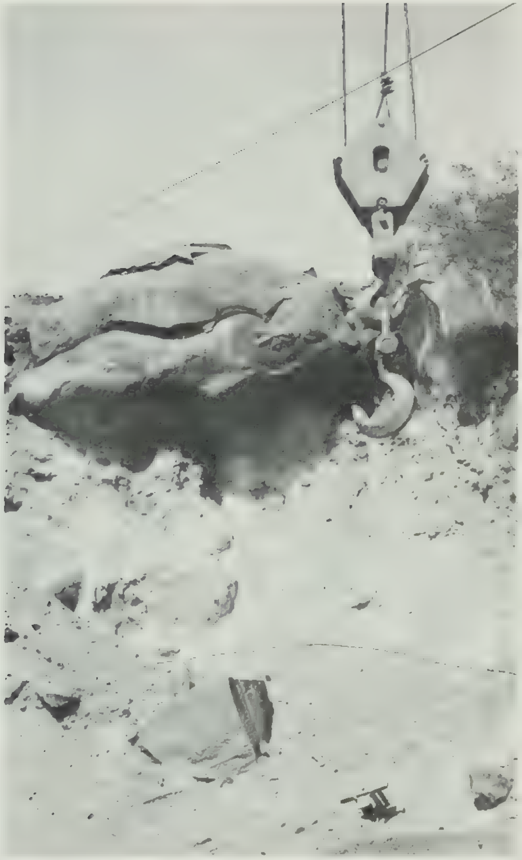


FIGURE 17. Residual boulders of hornblende norite in the Johnson (McGee) "black granite" quarry, Pala district. The dashed line indicates the base of a surface layer of "creep" debris, below which is partly weathered rock that has not been moved from its original position. Note the concentric spalling around the margins of some boulders.

The Agua Tibia fan must have been built so rapidly during late Pleistocene time that it choked the valley and dammed the San Luis Rey River, as fine-grained lacustrine deposits have been penetrated by numerous wells in Pauma Valley to the southeast. These deposits contain abundant plant fossils of Quaternary age. Later on, after the episode of major fan building had ended, the river breached the lower part of the fan and cut a trench as much as 350 feet deep. The rim of this trench is immediately south of the highway.

A large warm spring once issued from one of the breaks in the Elsinore fault zone at a point near the apex of the Agua Tibia fan. The main part of the fault zone crosses the high spurs and deep canyons about 2 miles east of the view point, and is in large part concealed by huge masses of slump and landslide debris.

114.3 Exposure of fine-grained, thinly and evenly bedded arkosic sand and silt. This material probably was deposited at the margins of the lake that once occupied Pauma Valley.

114.6 Pauma Valley. The scarp and well-defined benches ahead and to the left (east) are associated with the Elsinore fault zone. Some of the benches are underlain by landslide material.

117.2 Nigger Grade road. High on the slopes to the left (east) are broad benches that mark the trace of the Elsinore fault zone. Large slump and landslide masses are common in this area, which is underlain chiefly by schists and gneisses.

To the right (southwest and south), on the opposite side of the valley, are rugged slopes developed mainly on tonalite. Above them is an upland surface of low relief, which is mantled by soil and other residual material, as well as by local thin accumulations of alluvium.

119.3 Roadcut exposures show typical transitions between weathered and unweathered gabbro. This is one of the more felsic rock types that have been grouped with the San Marcos gabbro of the southern California batholith. A small excavation beyond the main roadcut exposes a thin pegmatite dike that can be traced continuously for a distance of more than a mile to the north.

Rincon Pegmatite District. Small quantities of gem beryl, spodumene, and tourmaline have been obtained from the pegmatite dikes of the Rincon district, which embraces an area of approximately 10 square miles. Most of the mining was done during the period 1903-11, and was restricted to only a few of the numerous dikes that are present in the area (Map 8). The geology and mineral deposits of the district have been treated in detail by Hanley (1951), and the complex mineralogy of the Victor pegmatite has been described by Rogers (1910).

As in the Pala district, the pegmatite occurs mainly as subparallel dikes that appear to have been emplaced along regional joints. In general they strike north-northwest and dip at moderate angles in a southwesterly direction. Unlike those of the Pala district, the Rincon dikes occur chiefly in plutons of tonalite, rather than gabbro.

Most of the dikes are mineralogically simple, and consist of quartz, perthite, and albite with subordinate muscovite and some accessory garnet, schorl, and beryl. Lithium-bearing minerals are present in only a few localities. The most abundant types of pegmatite are graphic granite, quartz-perthite pegmatite, massive quartz, and fine-grained, aplitic rocks that include typical line rock. The dikes ordinarily consist of three zones—a border zone, a wall zone, and a simple or segmented core. Other units of fine-grained rock, or of lithium-bearing pegmatite, occur locally. Few composite dikes have been recognized.

119.9 Rincon. Bear left (east) on State Highway 76.

A 5-mile side trip on the road to Escondido (bear right at Rincon) provides excellent exposures of the Bonsall tonalite, by far the most widespread rock type in this area. All gradations between weathered and unweathered rock can be seen in roadcuts on the grade south of the San Luis Rey River Valley. Residual masses of fresh tonalite are typically surrounded by disintegrated material (gruss) in which original textures and structures are remarkably well preserved (fig. 18); these masses have been referred to as "boulders of disintegration" by Larsen (1948, pp. 114-117). Many of the boulders represent the cores of original joint blocks, and where they rise above the surface of the ground they are grouped in regular patterns that reflect the original pattern of jointing.

120.0 State Highway 76 ascends the steep alluvial fan of Yuima and Potrero Creeks.

120.3 A ridge of bedrock beneath the surface of the fan in this area is an effective ground-water barrier, and much water is pumped from the basin above it for irrigation of avocado and citrus groves.

The rib-like projections of many pegmatite dikes appear low on the slope of Mesa Mountain at the left (north).

121.6 Directly ahead (north) are steep-walled natural cuts in sheared rock and landslide debris along the Elsinore fault zone. The main mountain mass is composed of tonalite that flanks a large septum of schist.

123.2 From this point to the top of the grade are many roadcut exposures of tonalite, schist, granodiorite, and hybrid gneisses.

124.3 Roadcut exposure of mafic Bonsall tonalite beneath lush growths of poison oak.

124.9 The highway traverses an irregular bench that is capped discontinuously by Quaternary gravels. The San Luis Rey River flows through a deep canyon about 2½ miles to the south (right).

125.2 Bear left for side trip to Palomar Mountain.

Palomar Mountain Side Trip

(1.1) Roadcut exposures of very coarse-grained alluvial-fan and landslide debris.

(1.6) The highway traverses an area underlain by fault-shattered tonalite, capped in places by landslide masses.

(2.2) Roadcut exposures of sheared and shattered rock in the Elsinore fault zone.

(2.7) Additional exposures of severely fractured tonalite and granodiorite, covered locally by very coarse-grained slump and slide deposits.

(3.2) The broad upland surface of the Mesa Grande appears to the southeast, beyond the canyon of the San Luis Rey River.

(3.6) The trees of the Agua Tibia Mountains clearly show the effects of altitude on the distribution of life zones. Here mixed stands of oak and Bigcone spruce appear in the canyons at an altitude of about 4,000 feet.

(4.0) Large exposures of shattered tonalite and hybrid schists and gneisses mark the major break that defines the Elsinore fault zone on the northeast.

(4.7) Roadcut exposures of Bonsall tonalite and foliated rocks of hybrid origin.

(5.0) Beginning of pine and cedar forest, although oak and spruce remain dominant at this level.

(5.5) Roadcuts expose foliated rocks of the Julian schist (Triassic?), which dip moderately to steeply east-northeast.

(6.0) Stand of small Coulter pine trees.

(6.9) Summit. Turn left (north).

(7.0) Junction with Ridge Road. Continue straight ahead on Observatory Road, which passes through heavy stands of incense cedar. Numerous roadcuts expose rocks of the Julian schist.

(10.3) The road crosses a swale that marks the trace of the south branch of the Agua Tibia fault, a longitudinal break that lies within the range.

(10.9) The road crosses the north branch of the Agua Tibia fault, whose general trace is marked in the area to the southeast by elongate shallow depressions and by aligned gulches and canyons.

(11.7) Palomar Observatory. The main observatory building houses the telescope with the famous 200-inch mirror. The museum and observation gallery are open to visitors daily from 8 A.M. to 5 P.M.

Retrace route to State Highway 76.

125.2 Continue eastward on State Highway 76.

127.2 Large cliff-making exposures of Woodson Mountain granodiorite are visible on both sides of the San Luis Rey River Canyon ahead and to the right (southwest). Several roadcuts expose Bonsall tonalite and associated hybrid gneisses.

128.5 The highway traverses an area in which very coarse-grained landslide debris conceals most of the bedrock.

129.4 Large roadcut exposures of thoroughly shattered and sheared rocks in the Elsinore fault zone. For the next 5½ miles the highway lies within this zone of severe disturbance, which has controlled the general course of the San Luis Rey River in this area.

132.9 San Luis Rey Campground.

134.6 Turn left (north) for side trip on Palomar Ridge Road.

Palomar Ridge Road Side Trip

(0.05) Cross the San Luis Rey River and Elsinore fault zone. Henshaw Dam, a large earth-fill structure, is at the right (east).

(0.5) Deep roadcuts expose shattered tonalite and granodiorite.

Warner Basin. The Warner Basin, also known as the Valle de San José, is a broad, saucer-like depression about 6 miles in diameter (fig. 17). It is separated from the Mesa Grande upland area on the southwest by a very steep scarp along the Elsinore fault zone, and from Hot Springs Mountain on the northeast by less prominent scarps associated with the Aguanga fault zone (Map 9). The Agua Tibia Mountains and Volcan Mountain rise to the northwest and southeast, respectively. The basin is transected by the Agua Tibia—Earthquake Valley fault zone, which bounds Volcan Mountain on the northeast.

The floor of the basin is underlain by alluvium and by arkosic valley fill of late Pleistocene age. The fill probably is correlative in age with parts of the fill in the Elsinore-Temecula trough. It rests upon plutonic igneous rocks, some masses of which project up through it as knobs and ridges, and it evidently was laid down upon a very irregular surface. In general it is thickest in the western part of the basin, and gives way in an eastward direction to a thin and discontinuous layer of gruss and residual boulders that lies directly upon crystalline rocks.

Sauer (1929, pp. 224-231) has divided the basin geomorphically into two parts, a southwestern area of Quaternary aggradation and a slightly larger northeastern area in which degradation has been the dominant process. The distribution of the upper Pleistocene fill suggests that this view may be somewhat oversimplified. Certainly the history of the basin is intimately related to movements, including some of lateral nature, along at least three major zones of subparallel faulting, and some transverse downwarping may have been involved, as well.

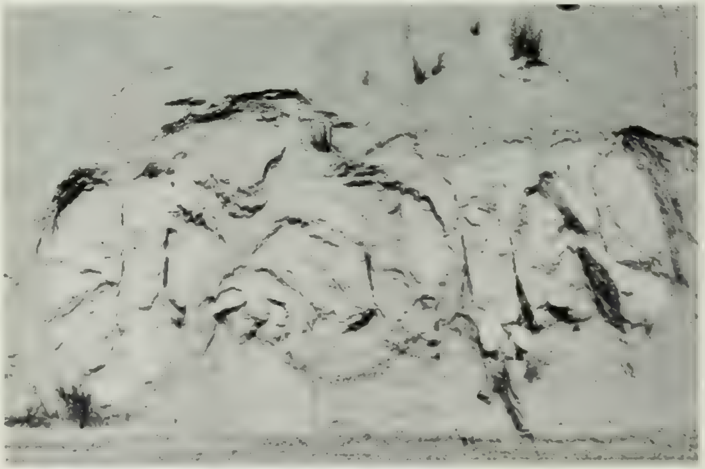


FIGURE 18. Weathered and unweathered Bonsall tonalite in roadcut about 4 miles south of Rincon. The fresh rock appears as large boulders of disintegration, which were drilled and blasted during excavation of the cut; the surrounding weathered rock was trimmed to a smooth face by means of shovels.

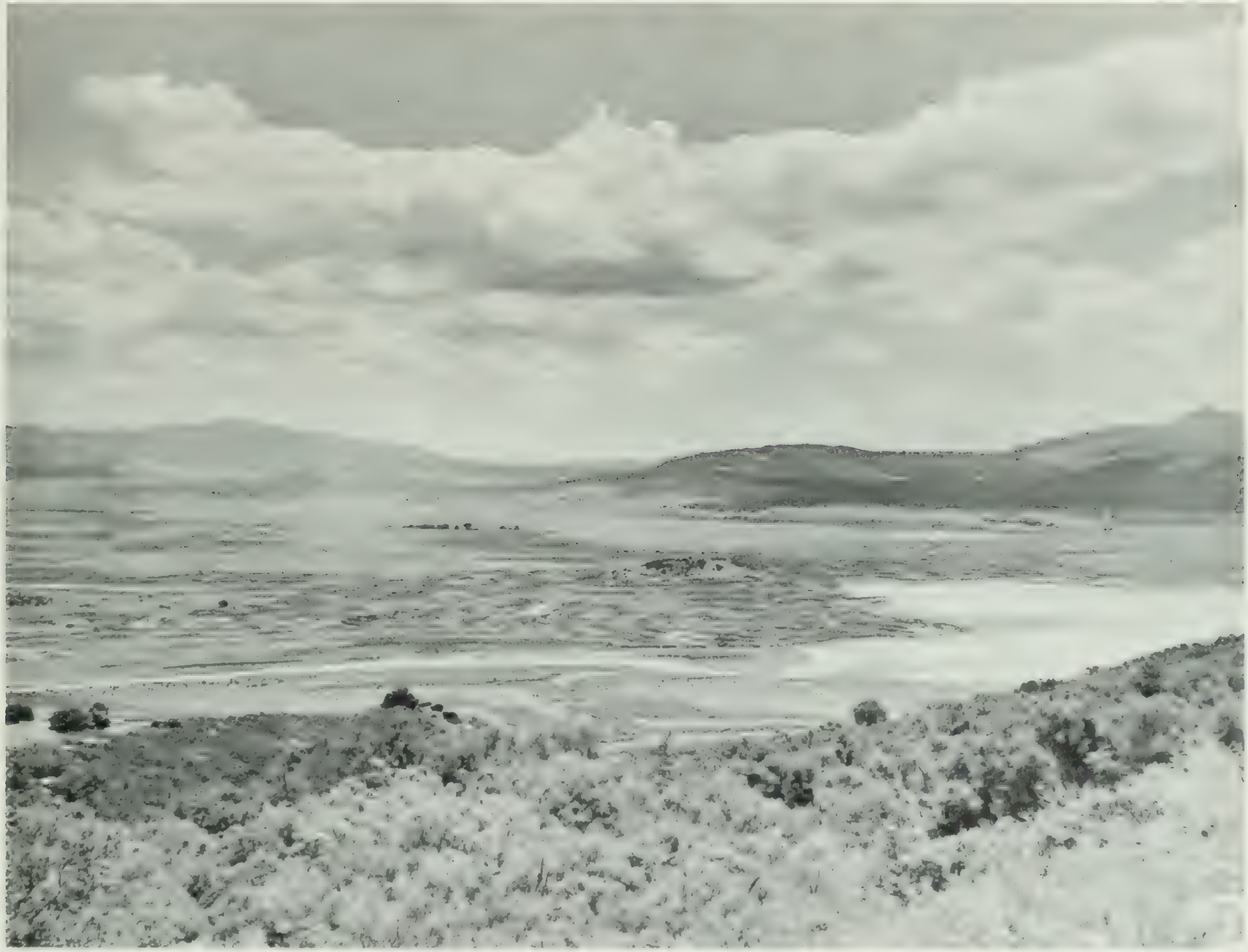


FIGURE 19. A part of the Warner Basin and Lake Henshaw, viewed southeastward from the end of the Agua Tibia Mountains. A dissected fill of upper Pleistocene arkosic sandstone and conglomerate occupies much of the lowland area. Shorelines corresponding to higher stages of the lake are outlined by stripes of vegetation in the middle distance. Volcan Mountain is at extreme right.

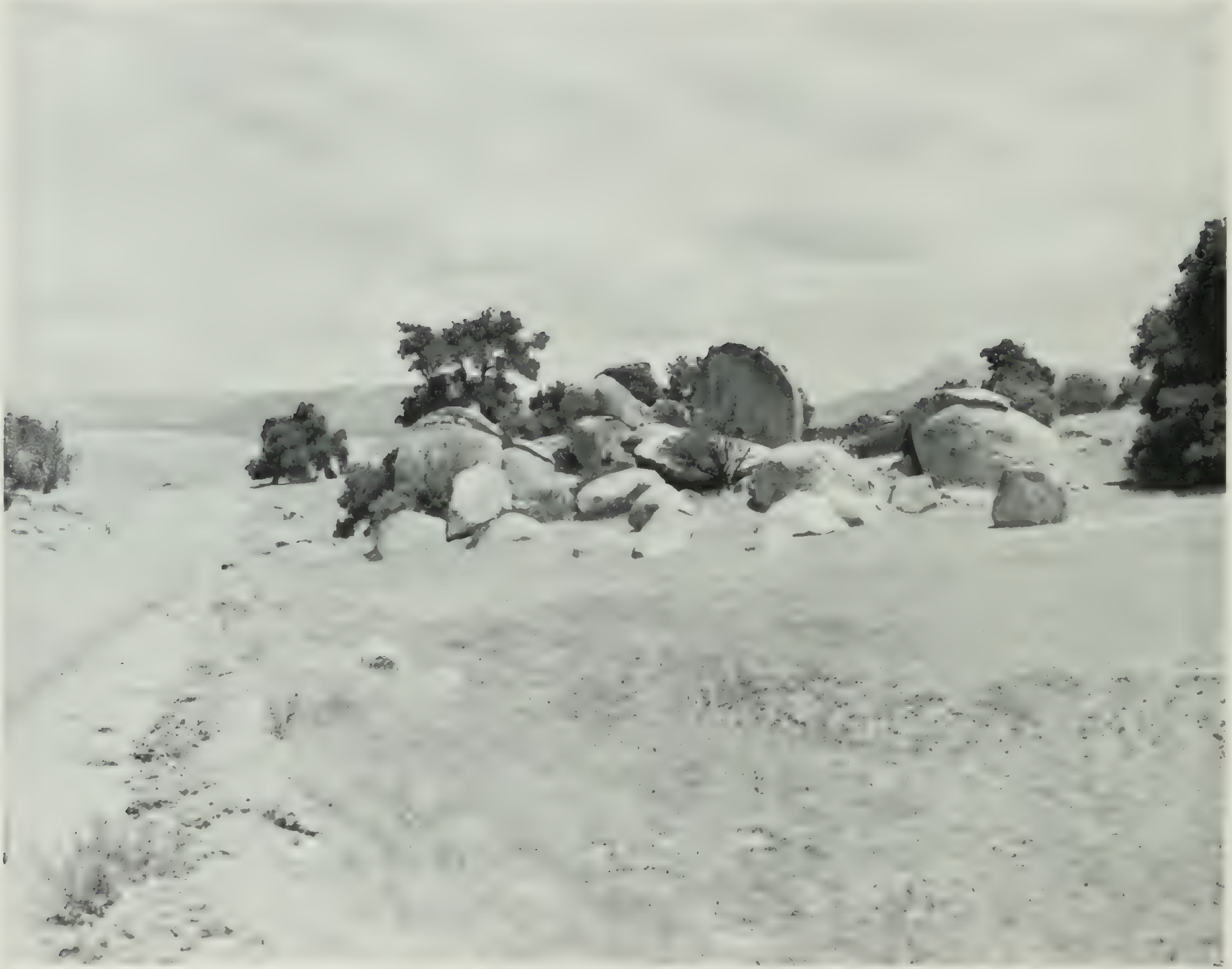


Figure 20. Large boulders of disintegration resting on a smooth bedrock surface, south side of the Warner Basin. The rock is the Lakeview Mountain tonalite.

(0.6) Broad view of the Warner Basin. The floor of the valley is occupied mainly by a dissected fill of poorly consolidated arkosic sandstone and conglomerate. Monkey Hill, a knob of tonalite, rises above the floor near the southeast end of Lake Henshaw. Abandoned shorelines of this reservoir lake are outlined by curving stripes of vegetation during periods of low water (fig. 19).

(2.0) View of the northern part of the Warner Basin and the mountains beyond. The bouldery, light-colored slopes in the distance to the northeast are underlain by coarse-grained granodiorite and felsic tonalite, and the darker-colored ridges are underlain by foliated rocks of possible Paleozoic age. The belt of metamorphic rocks terminates northwestward at Beauty Peak, visible near the left-hand end of the skyline ridge.

(3.2) Turn around and retrace route to State Highway 76.

134.6 Continue eastward on State Highway 76.

135.2 The small hill to the left (east) is an uplifted slice of upper Pleistocene arkose within the Elsinore fault zone. For the next 3 miles the highway traverses an irregular alluvial apron that skirts the southwest side of the Warner Basin. On the right is the steep scarp, known locally as "The Drop Off," that marks the northeastern edge of the Mesa Grande upland area.

137.0 Deep roadcut in foliated rocks of the Julian schist. Bear right onto old road for side trip to Mesa Grande.

Mesa Grande Side Trip

(0.2) Turn right (south) onto a narrow road that ascends The Drop Off. Exposed in numerous cuts on the 2-mile grade are schist, quartzite, and several varieties of hybrid gneiss, as well as tonalite and granodiorite that probably antedate the southern California batholith.

(1.9) Dumps of the old Shenandoah mine are at the right (northwest). This gold mine, like numerous other small mines in areas farther south, was developed in a lenticular quartz vein that cuts schist and gneiss.

(2.8) The road follows Scholder Creek, in a typical small valley of the Mesa Grande country. To the right (north) is Angel Mountain, which consists of gabbroic rocks and older foliated tonalite. Several roadcuts expose this tonalite, which has been correlated by Merriam (1946) with the Stonewall granodiorite of the Julian area to the southeast.

(4.3) Junction with road to the mines on Gem Hill.

Mesa Grande Pegmatite District. The pegmatite deposits of the Mesa Grande district, which occupies an area of about 2 square miles, have yielded an impressive amount of gem tourmaline, as well as small quantities of gem beryl, garnet, and quartz. The Himalaya and San Diego mines, on Gem Hill, probably have been the world's foremost source of gem and specimen tourmaline. Activities in the district were greatest during the priod 1902-12, and only a few mines have been worked intermittently since that time. Descriptions of the deposits have been published by Kunz (1905), Merrill (1914), Schaller (1922), and several other investigators.

As in the Pala and Rincon districts, most of the pegmatite occurs as subparallel dikes that trend north to north-northwest and dip moderately toward the west. At least 90 of these dikes are present within the district. They are enclosed mainly by gabbroic rocks.

The internal structure and lithologic units of the dikes are similar to those of the pegmatite bodies in the Pala district, although their average thickness is much less. The gem minerals occur typically in pocket pegmatite, chiefly in the central parts of a few dikes. In general, lithium-bearing varieties of tourmaline are more abundant than in the Pala district, whereas gem spodumene is relatively rare.

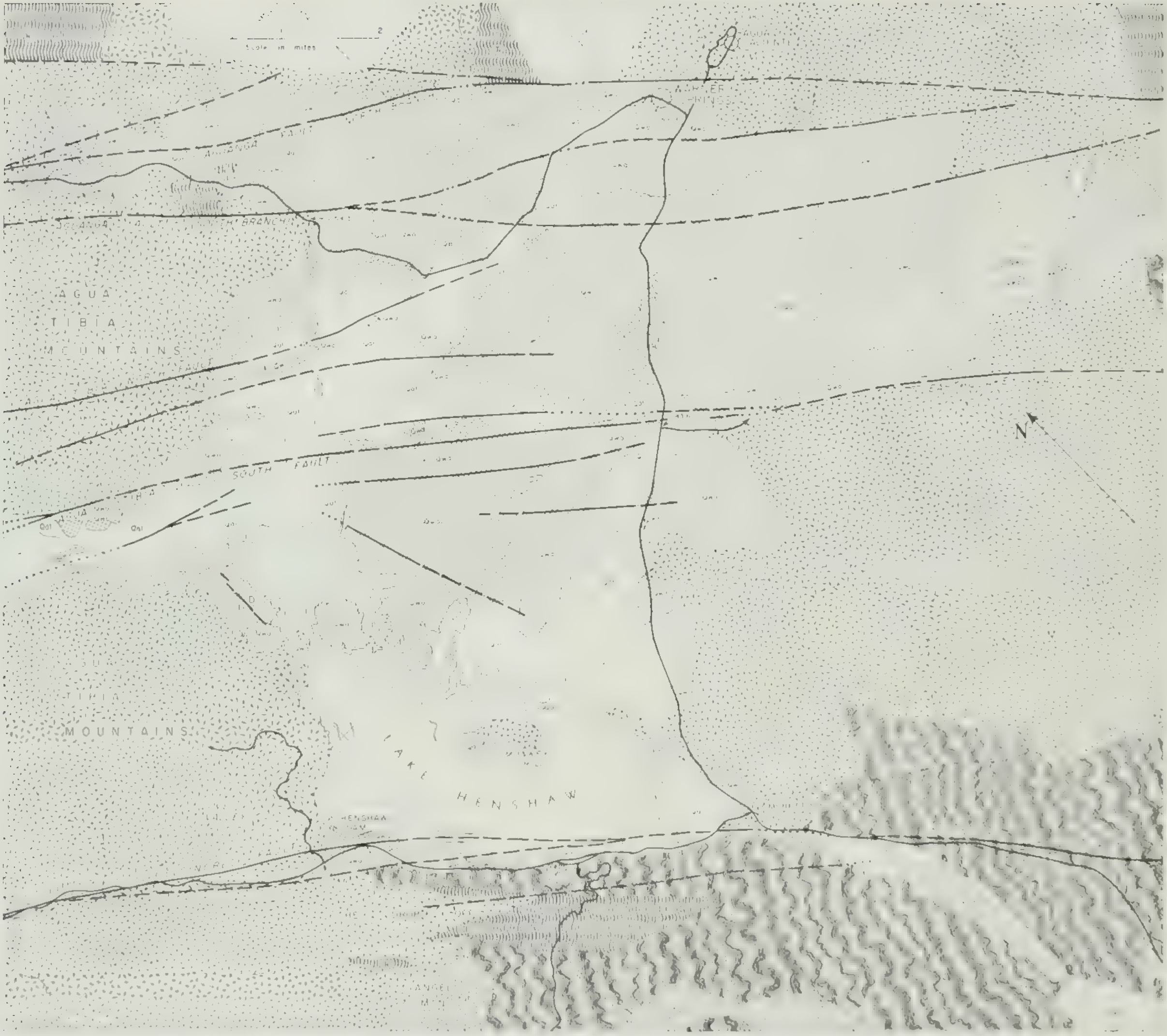
The principal gem deposits can be reached by road, as shown in Map 8, but travel over many of these roads by ordinary automobile is not recommended. With few exceptions, the underground workings of the mines are badly caved or are in otherwise unsafe condition, and they should not be entered.

(4.7) Mesa Grande school, and junction with road to mines west of Gem Hill.

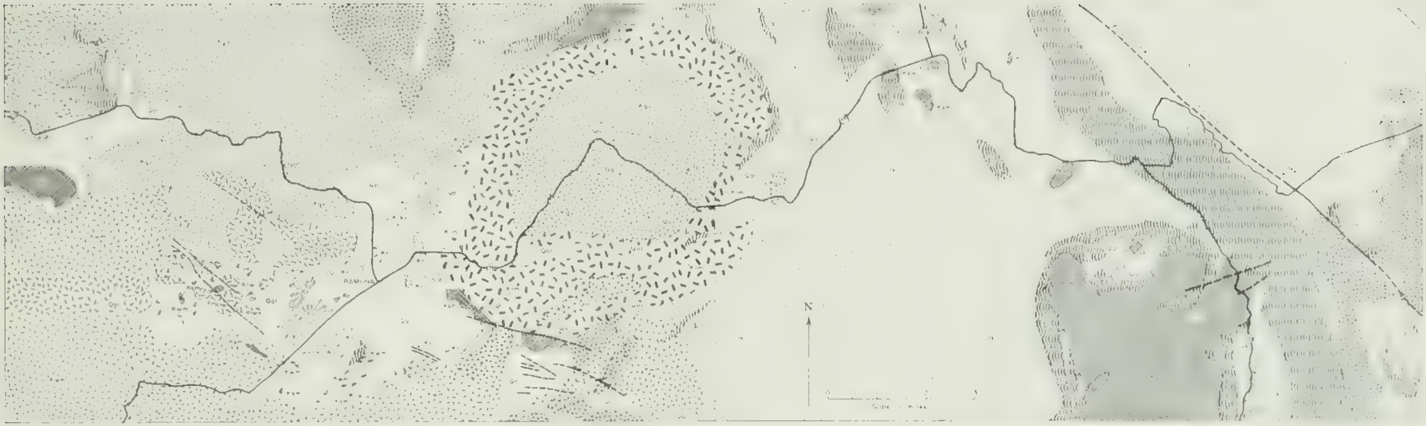
(5.5) Mesa Grande. Retrace route to State Highway 76, or continue southeastward 6.9 miles to State Highway 79 and thence 5.3 miles northward to rejoin the main route of travel at Morettis Corner.

137.0 Continue southeastward on State Highway 76.

138.3 Ahead is the valley of Carrista Creek, which marks the trace of the Elsinore fault zone. The slopes of Volcan Mountain, on the northeast side of the valley, are underlain by tonalite and granodiorite that probably are older than the rocks of the southern California batholith.



MAP 9. Warner Basin and adjacent areas. Qal—alluvium; Qwa—arkosic basin fill; Kt—tonalite; Kgb—gabbro and norite; Js—Stonewall granodiorite and associated schists, quartzite, and hybrid gneisses; Trj—Julian schist. See Table 2 for stratigraphic relationships and descriptions of these geologic units. *Geology by R. H. Jahns and Richard Merriam.*



MAP 10. Ramona-Julian area. Qal—alluvium and terrace deposits (Pleistocene and Recent); Tp—Poway conglomerate (Eocene); Kwm—Woodson Mountain granodiorite (Cretaceous); Klw—Lake Wolford granodiorite (Cretaceous); Kr—Ramona tonalite (Cretaceous); Kb—Bonsall tonalite (Cretaceous); Klm—Lakeview Mountain tonalite (Cretaceous); Kgv—Green Valley tonalite (Cretaceous); Ksm—San Marcos gabbro (Cretaceous); Js—Stonewall granodiorite and associated schists, quartzite, and hybrid gneisses (Jurassic ?); TRj—Julian schist (Triassic ?). *Geology by Richard Merriam.*

139.2 Morettis Corner; end of State Highway 76. Turn left (north) onto State Highway 79.

139.7 Roadcut exposures of well-bedded arkose and conglomerate. These upper Pleistocene beds lie on tonalite that is exposed immediately to the north. This crystalline rock, which is a part of the southern California batholith, weathers to form slopes that locally are very smooth.

142.0 Smooth slopes developed on felsic, quartz-rich tonalite that contains few inclusions. The rock in this general area has been correlated by Larsen (1948, p. 68) with the Lakeview Mountain tonalite of the Perris block to the northwest. Boulders of disintegration are scattered over parts of the area (fig. 20), and arkosic sediments lap against the bedrock in the low hills to the left (northwest).

143.1 An even terrace surface, underlain by upper Pleistocene deposits, is visible directly ahead.

143.6 Junction with highway to Borrego Valley. The trace of the Agua Tibia—Earthquake Valley fault zone is crossed here. Immediately beyond is a roadcut exposure of typical coarse-grained, cross-bedded arkosic sandstone and conglomerate.

146.8 Continue ahead (eastward) on the road to Agua Caliente.

147.0 The road crosses a depositional contact between the basin-filling sediments and a complex of tonalite and more basic intrusive rocks.

147.2 The Aguanga fault zone is crossed here. The crystalline rocks on the ridge at the right (southeast) have been thoroughly shattered and sheared. Continue up the canyon, keeping on the right-hand (upper) road.

148.3 Agua Caliente. Continue around loop and return to State Highway 79 via the lower road.

149.7 Turn right (north) onto State Highway 79.

149.9 Warner Springs.

Alternate loop from Pala to Warner Springs via Escondido, Ramona, and Julian—82.2 Miles

(Maps 8, 9, 10; Table 2)

This alternate route extends through a part of the Peninsular Range province that is relatively unbroken by large faults. It contains a wide variety of pre-Tertiary crystalline rocks, comprising numerous representatives of the southern California batholith, as well as older plutonic, metasedimentary, and metavolcanic rocks. The geology of large parts of this area has been described by Merriam (1946) and by Larsen (1948), and several of the principal rock types also have been discussed in detail by Donnelly (1934), Hudson (1922), Hurlbut (1935), F. S. Miller (1937), W. J. Miller (1946), and others.

(0.0-5.7) Pala to U. S. Highway 395, via State Highway 76. The road extends westward down the San Luis Rey River Valley, which is bordered on the north by gabbroic rocks and some tonalite, and on the south by tonalite and light-colored granodiorite. For the last mile of this segment of the route, the valley is flanked by leucogranodiorite that crops out boldly.

(5.7-21.5) San Luis Rey River to Escondido, via U. S. Highway 395. Numerous large roadcuts provide excellent exposures of weathered and unweathered leucogranodiorite, Bonsall tonalite, Woodson Mountain granodiorite, Santiago Peak volcanics, and, near Escondido, San Marcos gabbro (see map in Larsen, 1948).

(21.5-39.1) Escondido to Ramona, via State Highway 78. The route traverses an area underlain chiefly by the Green Valley tonalite, a medium-grained, medium gray, moderately mafic tonalite which in general lacks the dark inclusions that are so abundant in parts of the Bonsall tonalite. Much of the rock is deeply weathered.

(39.1-53.7) Ramona to Santa Ysabel, via State Highway 78. The western part of the area traversed is featured by a large ring-dike complex involving several varieties of tonalite (Merriam, 1941), and the eastern part is underlain principally by older tonalite, granodiorite, schist, and hybrid rocks (Map 10). In an area about 4 miles east-northeast of Ramona are several mines and prospects in pegmatite dikes that have yielded small amounts of gem beryl, garnet, topaz, and tourmaline.

(53.7-60.7) Santa Ysabel to Julian, via State Highway 79. Igneous and metamorphic rocks that antedate the southern California batholith are traversed on this segment of the route. The Julian district lies within a broad, northwest-trending belt of schists, quartzite, and gneisses that constitute the type Julian schist. These rocks may be in part correlative with the Triassic Bedford Canyon formation of the Santa Ana Mountains to the northwest.

Gold valued at about $6 million has been obtained from quartz veins that cut the foliated rocks in an elongate area that extends eastward and southeastward from the vicinity of Julian, and in a small area on the south side of Cuyamaca Lake, about 7 miles south of Julian. The mining activities were most vigorous during the periods 1870-76 and 1888-93, and only a small fraction of the total output from the district represents work done since 1900. According to Donnelly (1934), the veins contain tourmaline, mica, pyrite, pyrrhotite, arsenopyrite, gold, and petzite. The veins are typically interlayered with schist, are discontinuous, and have complex detailed structure.

Some nickel mineralization is associated with gabbroic rocks in an area about 3 miles south-southeast of Julian (Hudson, 1922; Creasey, 1946).

(60.7-82.2) Julian to Warner Springs, via State Highway 79. This segment of the route traverses an area underlain almost wholly by pre-batholith plutonic rocks and hybrid schists and gneisses before reaching the Warner Basin from the southeast.

Warner Springs to Anza—35.2 Miles
(Map 9; Table 2)

149.9 Leave Warnér Springs, traveling northward on State Highway 79.

153.4 Gently rolling country underlain by the arkosic fill of the Warner Basin.

154.5 The road crosses a ridge of tonalite, schist, and hybrid rocks that is bounded on the northeast by the south branch of the Aguanga fault zone. The San Luis Rey River, which drains the broad valley to the north, crosses this ridge in a short, steep-sided trench.

157.9 Upper part of Cañada Aguanga. The trace of the north branch of the Aguanga fault zone lies a few hundred feet to the right (northeast). Its position is marked by several springs and topographic sags. On the left (southwest) is a wide apron of alluvial material that was deposited on an irregular bedrock surface.

158.8 Holcomb Village. The broad floor of this pass between the drainages of the San Luis Rey River and Temecula Creek occupies the block between the north and south branches of the Aguanga fault zone, here about half a mile apart.

160.7 Huge ledges and bouldery exposures of coarse-grained hornblende-biotite tonalite. This is the Lakeview Mountain tonalite of the southern California batholith, and is very widespread in areas to the north and northwest.

162.7 The lower part of Dodge Valley lies ahead, and beyond it is the steep scarp of the Agua Tibia Mountains. Near the crest of the range, and about 3½ miles due south of this point, is the old Mountain Lily (Ware) mine, in which gem tourmaline and topaz were once obtained from pockets in an irregular pegmatite dike.

163.9 Oak Grove. This is the site of Camp Wright, which was occupied by the U. S. Army from 1861 to 1866 to guard communications between California and Arizona.

164.2 Site of the Oak Grove stage station, which was opened in 1858 on the Butterfield Overland mail route from St. Louis and Memphis to San Francisco. This stage line was operated for only three years.

Ahead and to the left (west-northwest) is a valley that marks the trace of the Aguanga fault zone. Northwestward from this area, Temecula Creek flows alternately through deep canyons cut in crystalline rocks and across broad valleys that have been alluviated by tributary drainage from the northeast. The steep slopes of the Agua Tibia Mountains are underlain chiefly by schist and quartzite in this area, whereas plutonic rocks are dominant in the lower hills and ridges north of the range.

In the mountainous area about 5 miles northeast of Oak Grove are several mines and prospects that have been developed in scheelite-bearing rock of contact-metamorphic origin. This tactite occurs between masses of calcareous metamorphic rocks, possibly of Paleozoic age, and tonalite of the southern California batholith.

167.8 San Diego-Riverside county line.

168.5 Aguanga Valley lies below and to the west. The lower part of its floor, which is covered with alluvium, rises gradually northward and northeastward into an area of terraces, beneath which are fault-bounded slices and blocks of tonalite (Cretaceous) and Temecula arkose (upper Pleistocene). Most of the faults trend west, and converge in this direction with the Aguanga fault zone.

170.0 Aguanga. Turn right (northeast) on road to Anza.

170.2 Roadcuts for the next 0.4 mile expose Temecula arkose that is cut by at least three subparallel faults with westerly trends.

171.6 Exposures of reddish brown upper Pleistocene conglomerate and sandstone. These strata dip about 5 degrees to the west, and lie upon a section of Temecula arkose that dips northwest at slightly higher angles.

172.1 To the left (west) is Lancaster Valley, on the south side of which a highly dissected area is underlain by the Temecula arkose.

172.5 A depositional contact between brownish upper Pleistocene alluvial-fan deposits and underlying tonalite is exposed in a roadcut. This tonalite, which crops out over a large area to the north and northeast, is finer grained and contains less hornblende than the typical Lakeview Mountain tonalite. It has been termed the Aguanga tonalite by Mann (1951).

173.9 Side road to Sage. The broad area of subdued relief to the left (north-northwest) is typical of several upland surfaces in the region between the Agua Tibia Mountains and the San Jacinto Mountains to the north.

176.4 The wide, alluvium-floored Coahuila Valley lies ahead. Its surface rises southeastward to higher parts of the broad Anza Upland, which are mantled by residual soil and accumulations of disintegrated tonalite. Northward beyond the valley is Coahuila Mountain, a large mass of schist and quartzite that encloses a smaller pluton of tonalite. This intrusive rock crops out on the south and southeast sides of the mountain, where it forms light-colored cliffs that contrast sharply with the more somber-appearing slopes that are underlain by the metamorphic rocks (fig. 21).

Numerous pegmatite dikes are present on and near Coahuila Mountain, chiefly within masses of tonalite and more basic intrusive rocks. Dikes on the south side of the mountain have yielded commercial feldspar and quartz, and several on its east side and on Little Coahuila Mountain to the northwest have been worked for lepidolite and gem tourmaline, beryl, and spodumene. Production from this area never was large, and most of the mines have been idle for many years.

183.5 Terwilliger Valley is ahead and to the right (southeast). It occupies a part of the widespread Anza Upland, and its alluvium-covered floor lies at a distinctly lower level than several nearby surfaces of low relief that have been developed on fine- to medium-grained tonalite and granodiorite. The general level of this area is about 2,000 feet higher than that of the Perris block to the northwest, and the problems of its geomorphic development and correlation with adjacent areas remain to be solved.

184.1 Exposures of highly sheared tonalite, which may mark the trace of a fault that some geologists have postulated as a bounding feature along the southwest side of Terwilliger Valley.

185.1 Anza.

Anza to Banning—47.9 Miles
(Map 11, Table 2)

185.1 Continue eastward on the highway through Anza.

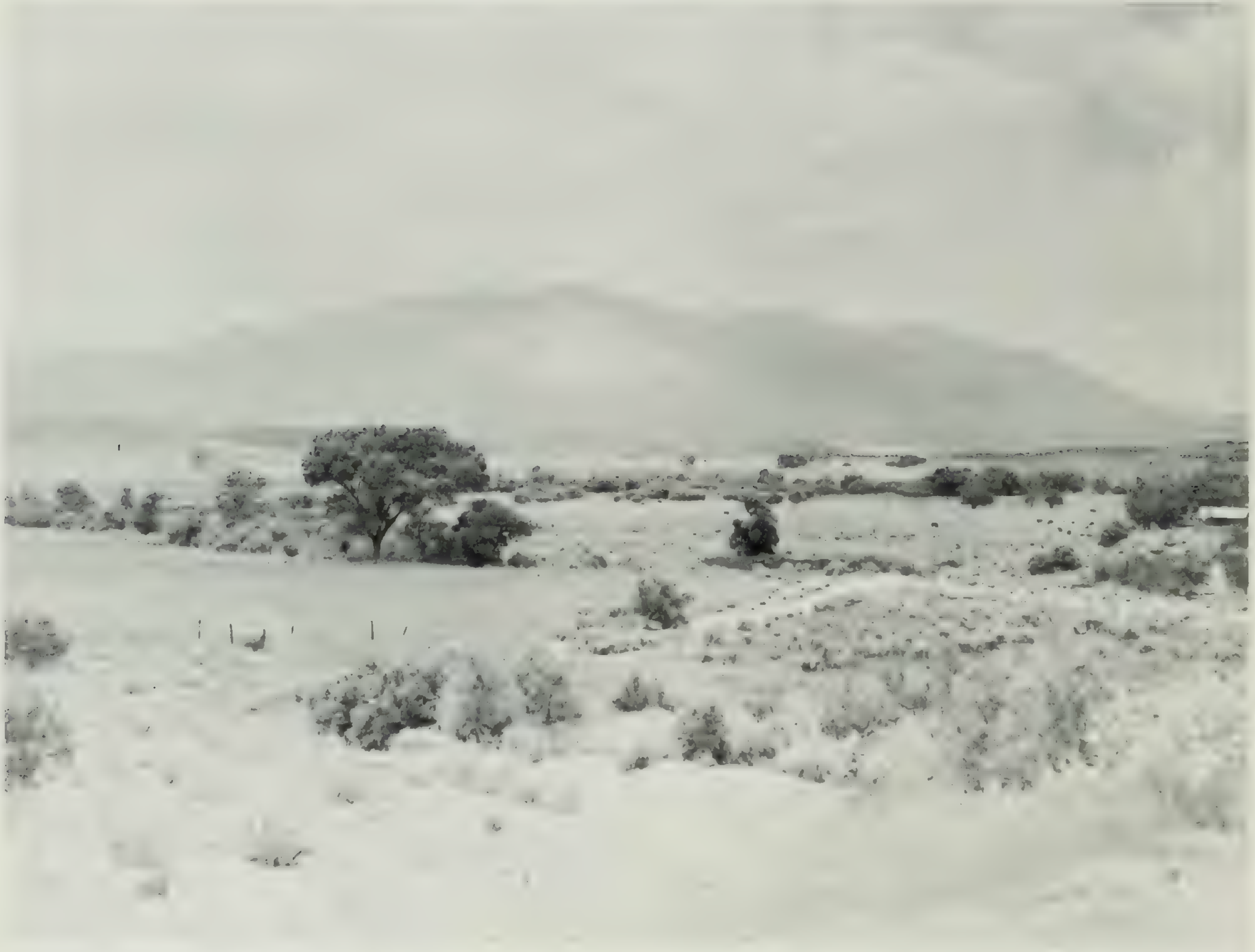


FIGURE 21. Coahuila Mountain, viewed from the southeast. A pluton of tonalite forms the prominent, light-colored cliffs, and the darker slopes are underlain by older schists and quartzite. The alluviated floor of Coahuila Valley, in the foreground, rises in the distance to a broad surface of erosion developed on tonalite and other crystalline rocks.

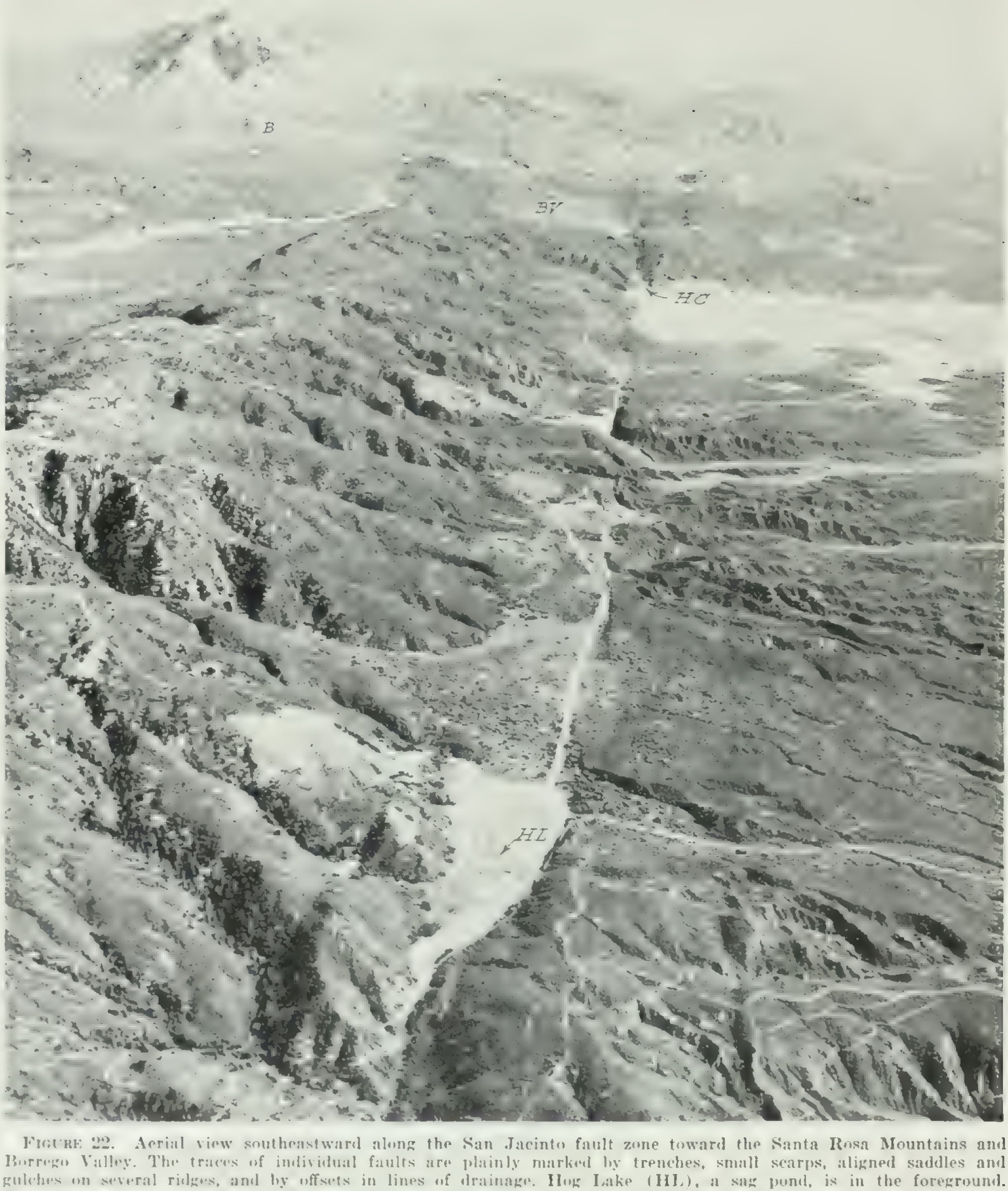


FIGURE 22. Aerial view southeastward along the San Jacinto fault zone toward the Santa Rosa Mountains and Borrego Valley. The traces of individual faults are plainly marked by trenches, small scarps, aligned saddles and gulches on several ridges, and by offsets in lines of drainage. Hog Lake (HL), a sag pond, is in the foreground. The Thomas Mountain ridge (TM), an elongate fault-bounded mass of tonalite, separates Hemet Valley at the left from the broad Anza Upland at the right. A thick section of upper Pleistocene arkosic deposits, the Bautista beds (B), is preserved at the upper end of Hemet Valley. Burnt Valley (BV), a small fault-flanked basin, lies beyond Hamilton Canyon (HC) in the middle distance. See Map 11 for the geology of this area. *Photo by J. S. Shelton and R. C. Frampton.*

185.6 Lookout Mountain rises as a distinct peak directly ahead. About 4½ miles to the left (north) is Thomas Mountain, a large mass of felsic tonalite that is bounded on both its northeast and southwest sides by major faults. High on the southwest slope of this mountain is the pegmatite dike in which gem tourmaline was first discovered and mined in California. The deposit was opened in 1872 and yielded some excellent gem material, but the mine has been idle for more than half a century.

San Jacinto Fault Zone. The San Jacinto fault zone, one of southern California's master breaks, diverges from the San Andreas fault zone on the north side of the San Gabriel Mountains. It extends southeastward across the San Bernardino Valley, along the southwestern margin of the San Jacinto Mountains, and through the area west, south, and southeast of the Santa Rosa Mountains into Imperial Valley. Its known length is approximately 180 miles.

In places the fault zone consists of one or more simple, well-defined breaks, especially where it cuts rocks of Tertiary or Quaternary age. More generally, however, it comprises several zones of subparallel to broadly anastomosing breaks separating masses of rocks that are profoundly shattered to almost undeformed. These fault-bounded masses range from slivers and slices a few feet thick to gigantic pinching-and-swelling slabs that are hundreds or even thousands of feet in maximum thickness (Map 11, fig. 22). Although they are parts of the San Jacinto zone, the faults and fault zones that define these larger masses are themselves major features, and commonly are given individual names.

The pattern of ramifying faults is especially broad in the area southwest of the Santa Rosa Mountains, where at least six major subparallel breaks are spaced half a mile to 3 miles apart. Indeed, the San Jacinto fault zone seems to widen southeastward into a series of very slightly diverging faults and fault zones that are separated by blocks of essentially unbroken rock, and hence loses its identity as a single zone or even as a single braid of zones. The Elsinore fault zone splits up in the same manner southeast of Elsinore, as does the San Andreas fault zone in the area north and east of San Bernardino.

The major breaks in the San Jacinto fault zone appear to dip very steeply, and the entire zone almost certainly is a very deep-rooted feature. Although it has not been studied in as much detail as the San Andreas fault zone (Noble, 1954), it seems to be similar to it in many respects. There is much evidence for vertical displacements both within and along the zone, and evidence for large-scale lateral movements has been reported from several areas (e.g., Dibblee, 1954). It seems probable that the San Jacinto fault zone is a major right-lateral break whose activities date back at least to early Tertiary time, but no meaningful estimate of the direction or amount of its net slip has been made as yet.

Some effects of the fault movements are beautifully expressed by elements of the present topography, which include scarps and scarplets, elongate trenches, sag ponds, anomalous benches and valleys, aligned gulches and canyons, and unusual patterns of drainage (fig. 22). Recency of movement is attested by some of these features, as well as by offset streams and records of numerous earthquakes.

188.0 The road enters the canyon of Hamilton Creek, which has been carved in the San Jacinto fault zone. Many roadcuts expose profoundly shattered and sheared schists, gneisses, and fine-grained tonalitic rocks. Zones of trituration are common.

188.8 The rocks in this area have been so thoroughly brecciated and crushed that they are readily eroded into badlands.

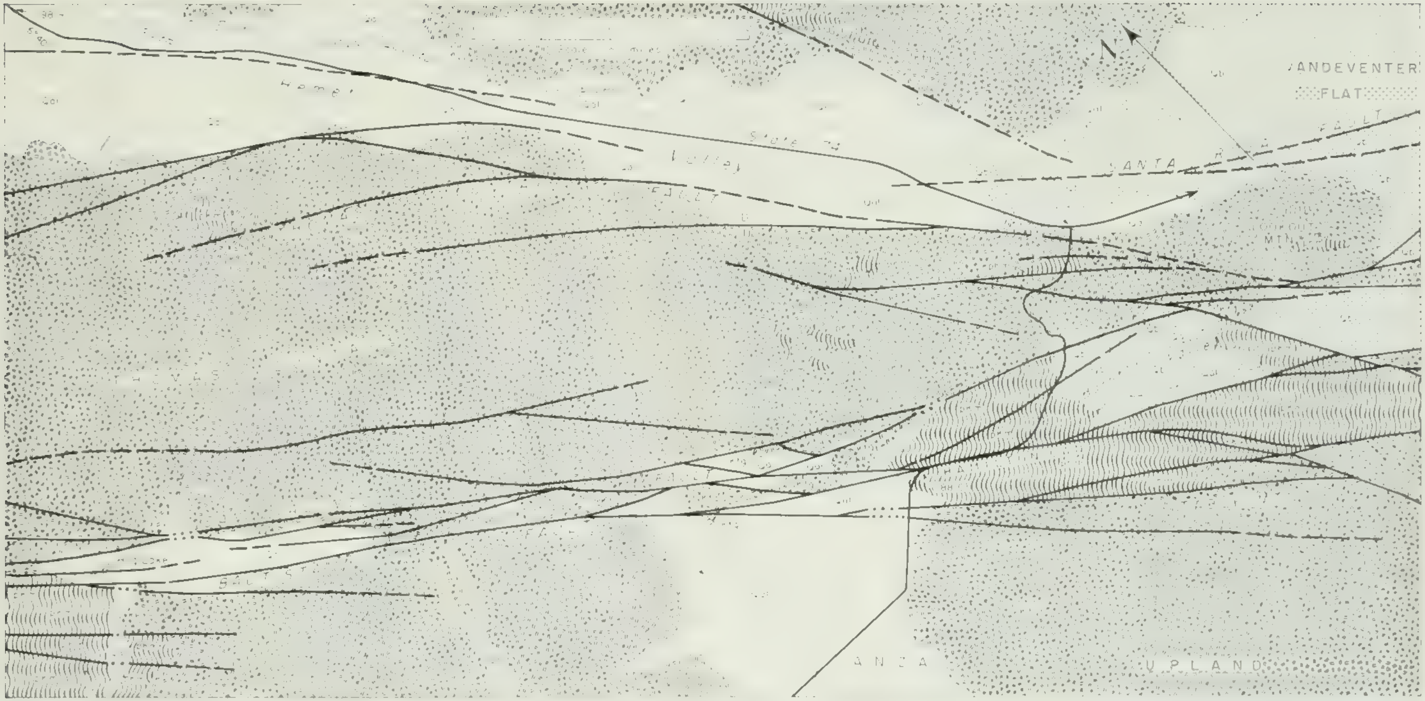
189.2 Roadcut exposures of severely disturbed schist that constitutes a block between two major zones of rupture. Beyond this are exposures of upper Pleistocene arkose.

189.9 Additional exposures of broken and sheared metamorphic rocks.

190.7 Summit.

191.0 Turn left (northwest) onto State Highway 74. About 0.1 mile to the left (southwest) is the trace of the Thomas Mountain fault zone, which here lies within a terrane of plutonic rocks but contains some slices of older metamorphic rocks. To the southeast, in the upper end of Hemet Valley, is a large remnant of upper Pleistocene arkosic deposits that once blanketed much of the valley floor. According to Fraser (1931, pp. 515-516), these deposits, which are as much as 500 feet thick, probably correspond to the Bautista beds in the area southeast of San Jacinto (Frick, 1921).

For the next 4 miles the highway traverses an apron of older alluvial-fan deposits that probably are in part correlative with the arkosic deposits to the southeast. They are concealed in many places beneath accumulations of younger alluvial debris.



Map 11. San Jacinto fault zone and adjacent areas, east of Anza. Qal—alluvium and terrace deposits (Pleistocene and Recent); Qb—Bautista beds (Pleistocene); Ktg—tonalite and granodiorite (Cretaceous); pKm—metamorphic rocks, chiefly schists and quartzite (pre-Cretaceous; possibly Paleozoic). *Geology by R. H. Jahns.*

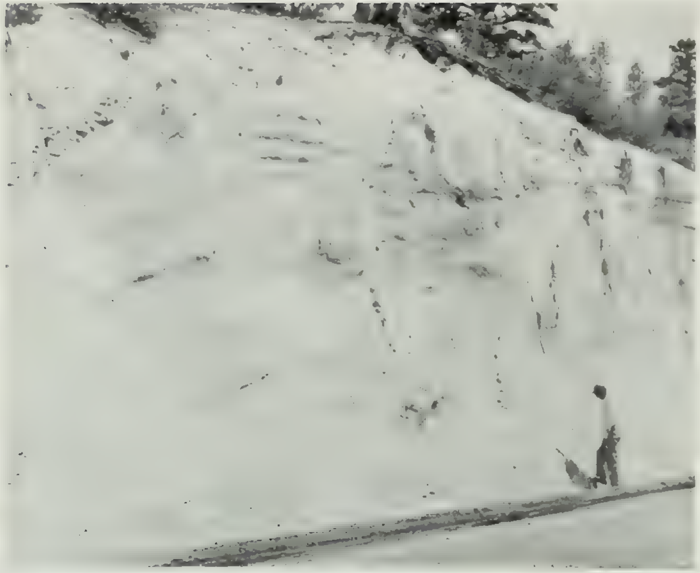


FIGURE 23. Roadcut exposure of coarse-grained tonalite, showing numerous mafic inclusions and irregular dikes and stringers of pegmatite. Idyllwild-Banning highway, on the west side of San Jacinto Peak.

197.4 The main mass of the San Jacinto Mountains rises ahead and to the right (north-northeast). It consists chiefly of plutonic rocks in the tonalite range, which probably are related to the southern California batholith. Older schists, gneisses, marble, and other metamorphic rocks appear as scattered inclusions, pendants, and septa, and also form one very large mass that crops out along the crest and east slopes in the southeastern half of the range.

Typical Lakeview Mountain tonalite is well exposed on the opposite side of Hemet Valley. This rock underlies nearly all of the mountain slope, and is in contact with the older metamorphic rocks at and near the top of this slope.

199.1 Hemet Reservoir, at the left (west), occupies the lower end of Hemet Valley. The elongate valley evidently owes its anomalous form and position to the Thomas Mountain fault along its southwestern margin, and possibly to another zone of faulting near its northeastern margin. It may have been occupied by a lake during a part of late Pleistocene time, and it is now tapped by the deep gorge of the South Fork of the San Jacinto River, most of which has been excavated along the Thomas Mountain fault zone.

200.6 Several roadcuts expose landside deposits that contain gigantic fragments of plutonic rock. This material was derived from the scarp of the Hot Springs fault, a break that is parallel to the Thomas Mountain fault and about 2 miles northeast of it.

201.9 Keen Camp summit, elevation 4,917 feet.

203.6 Turn right (north) onto Idyllwild-Banning highway.

207.6 Bear left and continue on the main road.

208.1 Idyllwild. Continue through town. For the next 12 miles the road skirts the highest part of the San Jacinto Mountains, passing through rugged country that is forested with oak and pine.

Numerous roadcuts expose medium- to coarse-grained felsic plutonic rocks, chiefly the Lakeview Mountain tonalite. Inclusions of more mafic rock are abundant in some areas, and small, irregular dikes of aplite and pegmatite are widespread (fig. 23). Much of the tonalite is weathered to depths of 10 feet or more, and yields gruss-covered slopes with numerous boulders of disintegration. Transitions between weathered and unweathered rock are exposed in many of the roadcuts.

211.0 Pine Cove.

213.6 Road to upper camp area.

217.7 Excellent view of San Jacinto Valley to the left (west).

218.2 Lake Fulmor. For the next 7 miles the road crosses an area that is underlain chiefly by very light gray, medium-grained, quartz-rich granodiorite.

222.3 First view of the San Gorgonio Pass area, with the San Bernardino Mountains in the distance to the north. Hurley Flat lies below and about 2 miles northeast of the view point.

224.2 Side road to Poppet Flat.

226.0 The road traverses a rugged area that is underlain by fine- to medium-grained leucocratic tonalite that resembles the tonalite of the Aguanga area to the south.

228.5 Excellent panoramic view of the San Gorgonio Pass area (fig. 24).

San Gorgonio Pass. San Gorgonio Pass is essentially a deep, nearly flat-floored trench that separates two of the highest mountain ranges in southern California. It trends east-

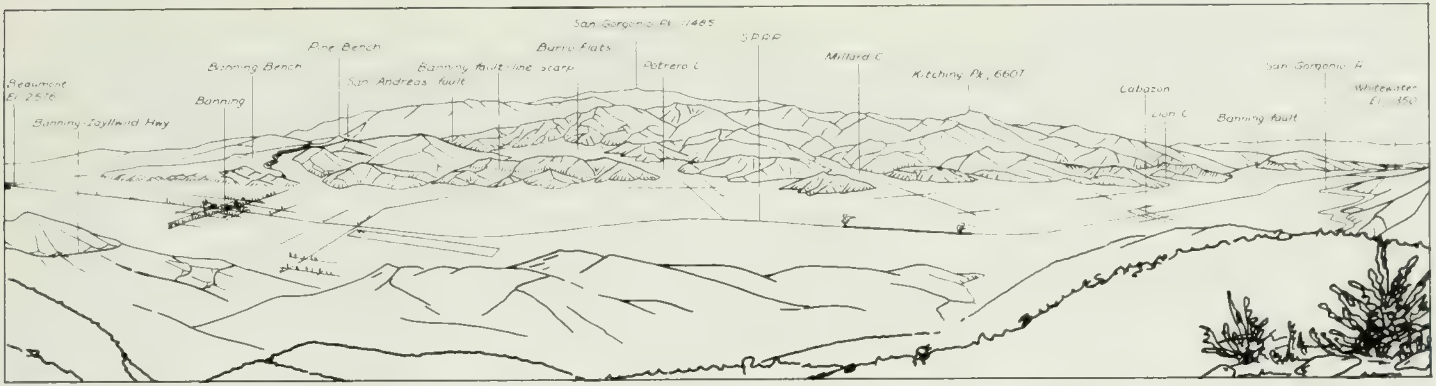


Figure 24. San Gorgonio Pass and the San Bernardino Mountains, viewed northward from the San Jacinto Mountains. A narrow and irregular strip of upper Tertiary and Quaternary rocks fringes the pass on the north, and is in fault contact with the gneisses and other crystalline rocks of the San Bernardino Mountains beyond. *Sketch prepared by Clarence R. Allen.*

west, and is bounded on the south by the impressive scarp of the San Jacinto Mountains. On its north side the foothills of the San Bernardino Mountains occupy an area of great topographic irregularity and complex structure. Exposed along the southern margin of this foothill area is a sequence of nonmarine sedimentary rocks that reflects a history of recurrent deformation and fluviatile deposition during late Tertiary and Quaternary time. A thin unit of marine strata attests the northwestward incursion of waters from the Gulf of California area early in Pliocene time.

The pass and the foothills north of the pass occupy an area in which faults of the northwest-trending San Andreas zone and faults with the characteristic east-west trend of the Transverse Range province intersect with and butt against one another to form an intricate mosaic of juggled blocks and slices. Involved in this faulting are the crystalline rocks of the San Bernardino Mountains, comprising plutonic types of Mesozoic age and gneisses and schists that may be in part much older. The dissimilar plutonic and metamorphic rocks of the San Jacinto Mountains seem to lie south of the zone of major disturbance.

The Banning fault zone is the principal structural break that is exposed within the pass area. It trends westward and west-northwestward along the north side of the pass (fig. 24), where it brings sedimentary rocks of Cenozoic age into contact with the older crystalline rocks to the north throughout the 25-mile interval between Whitewater Canyon and Yucaipa Valley west of Beaumont, and it probably extends still farther west to the San Jacinto fault zone (Allen, 1954). It is a vertical or steep reverse fault except in the vicinity of Millard Canyon (fig. 24), where there is a zone of low-angle thrusting from the north.

The break that has been termed the San Andreas fault in the pass area extends in a southeasterly direction across Pine Bench and Burro Flats, and thence appears to swing abruptly south and butt into the Banning fault zone near the mouth of Potrero Canyon (Allen, 1954). The Mill Creek fault, Mission Creek fault, and other members of the San Andreas zone lie farther north within the area shown in figure 24. Allen (1954) has noted that the San Andreas fault zone in the San Gorgonio Pass area is distinguished by several unusual features, and that there is little evidence for the very large-scale lateral displacements that have been deduced in areas to the northwest (e.g., Hill and Dibblee, 1953; Noble, 1954).

At least a mile of vertical displacement along the Banning fault since Pliocene time is indicated by the distribution and thickness of sedimentary rocks south of this break (Allen, 1954), and right-lateral offsets of somewhat greater total magnitude are suggested by less direct evidence. Earlier displacements may have been much larger. A fault similar to the Banning fault probably bounds San Gorgonio Pass on the south, but its trace is buried beneath thick alluvial-fan deposits of Quaternary age. The pass seems to owe its present form much more to vertical displacements along faults than to erosion. Warping may well have been important also, and even some of the Quaternary gravels in this area have been gently folded. Repeated uplift of the San Gorgonio Mountains is attested by unconformities within the Cenozoic section, and by the present relative positions of several well-defined terraces on the north side of the pass.

231.9 Base of the grade. The road crosses the alluviated floor of the pass. The Quaternary fan deposits derived from the San Bernardino Mountains dominate those derived from the San Jacinto Mountains, and hence the longitudinal drainage through the pass area lies against the base of the latter range.

233.0 Banning, San Gorgonio Avenue and Ramsey Street (U. S. Highway 60-70-99).

Whitewater Canyon Side Trip

(0.0) Turn right (east) onto U. S. Highway 60-70-99.

(1.0) The hills about 2 miles to the north (left) are underlain by Pliocene or lower Pleistocene sedimentary and volcanic rocks. The Banning fault separates this section from coarse-grained gneiss that crops out on the higher slopes.

(2.9) The mouth of Potrero Canyon is to the left (north). In this area the San Andreas and several other fault zones butt into the Banning fault zone, which itself is offset by a cross fault about half a mile west of the canyon. The prominent hill 1½ miles ahead and to the left (northeast) is underlain by Pleistocene fanglomerate.

(6.1) Cabazon. The Banning fault zone traverses the steep-sided foothills about 2 miles to the north, where it includes large slices of Pliocene or lower Pleistocene nonmarine strata that are bounded on the south by younger fanglomerate and on the north by coarse-grained gneiss.

Near the base of the San Jacinto scarp, about 1½ miles southeast of Cabazon, is the north portal of the Metropolitan Water District tunnel through the mountains to the San Jacinto Valley. This 13-mile tunnel is a part of the Colorado River aqueduct to the Los Angeles and San Diego regions.

(8.8) Side road that extends northeastward to the mouth of Stubby Canyon, where the Banning fault zone includes low-angle thrusts along which gneiss and other crystalline rocks have moved southward over upper Tertiary and Quaternary sedimentary rocks. This zone of thrusting is traceable for a distance of approximately 2 miles eastward along the base of the foothills.

(12.0) Junction with State Highway 111. Bear left and continue on U. S. Highway 60-70-99. Ahead and to the left (northeast) is Whitewater Hill, a large mass of Pleistocene fanglomerate that is separated by the Banning fault from highly deformed gneisses to the north. The fault in this area dips to the north at angles of 50 to 65 degrees.

(14.0) Bear left onto old road to Whitewater.

(14.3) Turn left (north) onto Whitewater Canyon road. Beacon Hill, 1½ miles to the east, is a mass of Pleistocene fanglomerate that has been warped into a broad anticline.

(15.8) The Banning fault, which commonly has been termed the San Andreas fault in this area, crosses Whitewater Canyon. Its effect on ground-water distribution can be inferred from the growth of vegetation upstream from its projected trace on the canyon bottom. The fault dips steeply north in this area, and on the east wall of the canyon it separates Pleistocene fanglomerate on the south from gneiss that is overlain by deformed conglomerate on the north. This conglomerate probably is older than the rocks exposed on the south side of the fault.

West of the canyon the fanglomerate on the south has been faulted against profoundly crushed and sheared gneiss and schist. The fault zone is well exposed in the side canyon that drains from the west, and can be observed by means of an easy traverse on foot.

Retrace route to Banning.

Banning to Riverside—30.8 Miles

233.0 Leave Banning in a westward direction on U. S. Highway 60-70-99.

234.2 About a mile to the right (north) is a large, well-defined terrace, the Banning Bench, which is capped by fanglomerate. Beneath this coarse-grained deposit are north-dipping beds of Pliocene or lower Pleistocene sandstone and conglomerate.

237.7 The road crosses Smith Creek, which flows southward down the eastern part of a broad alluvial fan and thence eastward through San Gorgonio Pass as part of the Coachella Valley drainage. The western part of this same fan is occupied by creeks that drain westward to the San Bernardino Valley via San Timoteo Canyon. A small part of the fan southwest of the view point is drained by Potrero Creek, which flows south-

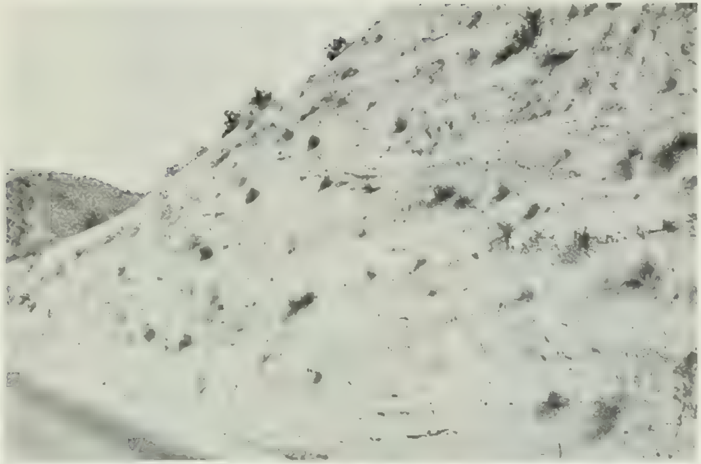


FIGURE 25. Interbedded conglomerate, sandstone, and siltstone of the upper Pliocene San Timoteo formation, U. S. Highway 60 south of San Timoteo Canyon. Note the offsets along faults in the left-hand part of the view.

ward through the low western part of the San Jacinto Mountains into San Jacinto Valley (fig. 1).

238.7 Summit of San Gorgonio Pass, elevation 2,616 feet. This inconspicuous crest is merely a high point on the transverse profile of the broad alluvial fan that has been built southward across a part of the pass area by drainage from the San Bernardino Mountains.

239.6 Turn left (west) onto U. S. Highway 60.

240.6 The highway crosses a broad terrace that is underlain by reddish-brown alluvial-fan deposits of probable late Pleistocene age.

242.8 For the next 1½ miles the route follows the southwestern margin of San Timoteo Canyon. The hills on both sides of this canyon are underlain by upper Tertiary nonmarine sedimentary rocks.

245.1 Conglomerate, arkosic sandstone, and siltstone of the upper Pliocene San Timoteo formation (Frick, 1921, 1933) are exposed in badlands to the right (north). An extensive badlands area to the south is underlain in part by these buff to gray strata, and in large part by strata of the lower Pliocene Mount Eden formation (Axelrod, 1937, 1950; Fraser, 1931; Frick, 1921, 1933, 1937), which are finer grained and commonly variegated.

245.6 Roadcut exposures of interbedded siltstone, sandstone, and lenticular conglomerate. Cut-and-fill structure is widespread, and the strata are broken by numerous faults of small displacement (fig. 25).

248.2 Junction with State Highway 79. To the left (south and southeast) is the nearly flat-floored San Jacinto Valley.

248.5 Prominent scarp that marks one of the main breaks in the San Jacinto fault zone. This active fault separates valley alluvium on the southwest from Pliocene nonmarine strata on the northeast. To the left (south) is Mt. Russell, a mass of medium- to coarse-grained Bonsall tonalite.

250.4 The highway crosses the trace of a major fault that bounds Mt. Russell on its northeast end. This fault, one of several in the San Jacinto zone in this area, evidently has been active during Recent time. Its trace on the valley floor to the southeast is marked by subdued trenches, offset drainage lines, and upthrown slices and wedges of Quaternary deposits.

251.7 Roadcut exposures of weathered tonalite.

253.0 On the left (south and southwest) is Moreno Valley, which forms the northeastern part of a very broad area of low relief. This and adjacent valleys, together with old erosion surfaces and small mountain masses at higher levels, are known collectively as the Perris Upland. The complex geomorphic history of this large area is yet to be deciphered completely, especially as it relates to adjacent areas; it has been discussed by Dudley (1936), Larsen (1948, pp. 8-15), and others.

255.5 Ahead and to the right (northwest) are the Box Springs Mountains, a large mass of Bonsall tonalite.

257.9 Junction with U. S. Highway 395.

258.1 Bridge over Santa Fe Railway. To the right (north) is the bold southwest face of the Box Springs Mountains. A zone of crushed and sheared rock along the base of this scarp suggests the presence of a northwest-trending fault.

258.9 The large quarry at the right (east) has been worked mainly for rip rap.

259.8 Mt. Rubidoux, which is underlain by leucogranite of the southern California batholith, rises above the valley floor directly ahead. Farther in the distance and slightly to the right are the Jurupa Mountains, which consist of plutonic rocks and irregular masses of older metamorphic rocks (MacKevett, 1951). The igneous rocks of this small range are the northernmost exposed representatives of the southern California batholith.

263.8 Riverside, Eighth Avenue and Main Street.

Riverside to Los Angeles—58.3 Miles
(Maps 1, 2; Table 1)

263.8 Continue westward through Riverside on U. S. Highway 60, and skirt the northern end of Mt. Rubidoux on the west side of the city.

265.0 Bridge over Santa Ana River.

266.0 Turn right (northeast) onto Bloomington Avenue. The main mass of the Jurupa Mountains rises to the left (west).

266.8 Directly ahead is the remnant of a once-prominent hill that has been quarried for nearly half a century by the Riverside Cement Company.

268.4 Crestmore plant of the Riverside Cement Company.

The Crestmore Hills.[*] The mine and quarries at the Crestmore Hills, about 3 miles north of Riverside, have yielded many millions of tons of limestone for the manufacture of cement since the first quarry was opened on Chino Hill in 1908 by the Riverside Portland Cement Company. Quarrying operations later were extended to the north side of Sky Blue Hill, the northeastern of the twin hills (figs. 26, 27), and the North Star, Lone Star, and Wet Weather quarries were successively opened. During World War II the old North Star and Lone Star quarries were nearly obliterated by westward extension of the Wet Weather quarry. Rip rap was taken from the Commercial quarry on the east side of Sky Blue Hill beginning about 1912, and not until recent years has limestone from this opening been used for the manufacture of cement. The Crestmore mine, in which a modified block-caving system of mining eventually was employed, was opened about 1930 beneath the floor of the Chino quarry, between the two hills. Most of the production of limestone at Crestmore during the past two decades has been from this mine.

The many quarry exposures and mine openings, together with tens of thousands of feet of diamond-drill cores, have presented an unusual opportunity for highly detailed studies of the compositions, spatial positions, and time relationships of the highly complex rock and mineral assemblages in this small area.

The limestone at Crestmore occurs chiefly as two crudely lenticular bodies. The lower or Chino limestone has been exploited in the Chino quarry and the Crestmore mine, and the upper or Sky Blue limestone has been worked in the other quarries. These two bodies are parts of a thick series of predominantly siliceous metasedimentary rocks that probably are of late Paleozoic or early Mesozoic age. These metamorphic rocks trend slightly west of north and dip moderately eastward in this area; locally beneath Sky Blue Hill, however, both limestone bodies have been deformed into a shallow syncline that plunges eastward. A section of siliceous metasedimentary rocks that probably did not exceed 200 feet in original thickness separates the Sky Blue limestone from the Chino limestone, and in general is conformable with them.

This section of older rocks occurs as a large screen in the Bonsall tonalite of the southern California batholith, which is the principal rock type in the area west and south of Crestmore. The tonalite also is present as sill-like bodies in the siliceous rocks between the two masses of limestone. Intrusion was accompanied by considerable plastic deformation in the upper parts of the Chino limestone and in the lower parts of the Sky Blue limestone, and in places this deformation was severe enough to pinch off the Chino limestone along an east-west line in the southern part of the area.

Metamorphism associated with the intrusion of the Bonsall tonalite consisted of: (1) conversion of the pure limestone beds into a coarse-grained, white to gray calcite marble, (2) conversion of the interbedded magnesian limestones into periclase marbles that subsequently were altered to predazzites, (3) metasomatic alteration of about a foot of limestone at the contact to a diopside-wollastonite-grossularite rock, (4) conversion of the less calcium-rich siliceous sediments into feldspathic hornblende and biotite-bearing quartz gneiss, hornfels, and schist, and (5) conversion of the more calcium-rich siliceous sediments into pyroxene hornfels and gneiss, and locally into wollastonite-bearing gneiss and schist.

Subsequently, the part of this suite of igneous and metasedimentary rocks that underlies Sky Blue Hill and the Commercial quarry was intruded by a relatively small pipe-like mass of aplitic quartz monzonite porphyry. The porphyry magma appears to have entered the area of the quarries from the southeast, and to have been intruded upward and northward through the tonalite to the contact with metasedimentary rocks, and thence mostly westward up the dip of these rocks beneath the Commercial quarry and Sky Blue Hill. The porphyry does not appear to have extended more than about

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[*] This statement was kindly furnished by C. Wayne Burnham, of the California Institute of Technology.

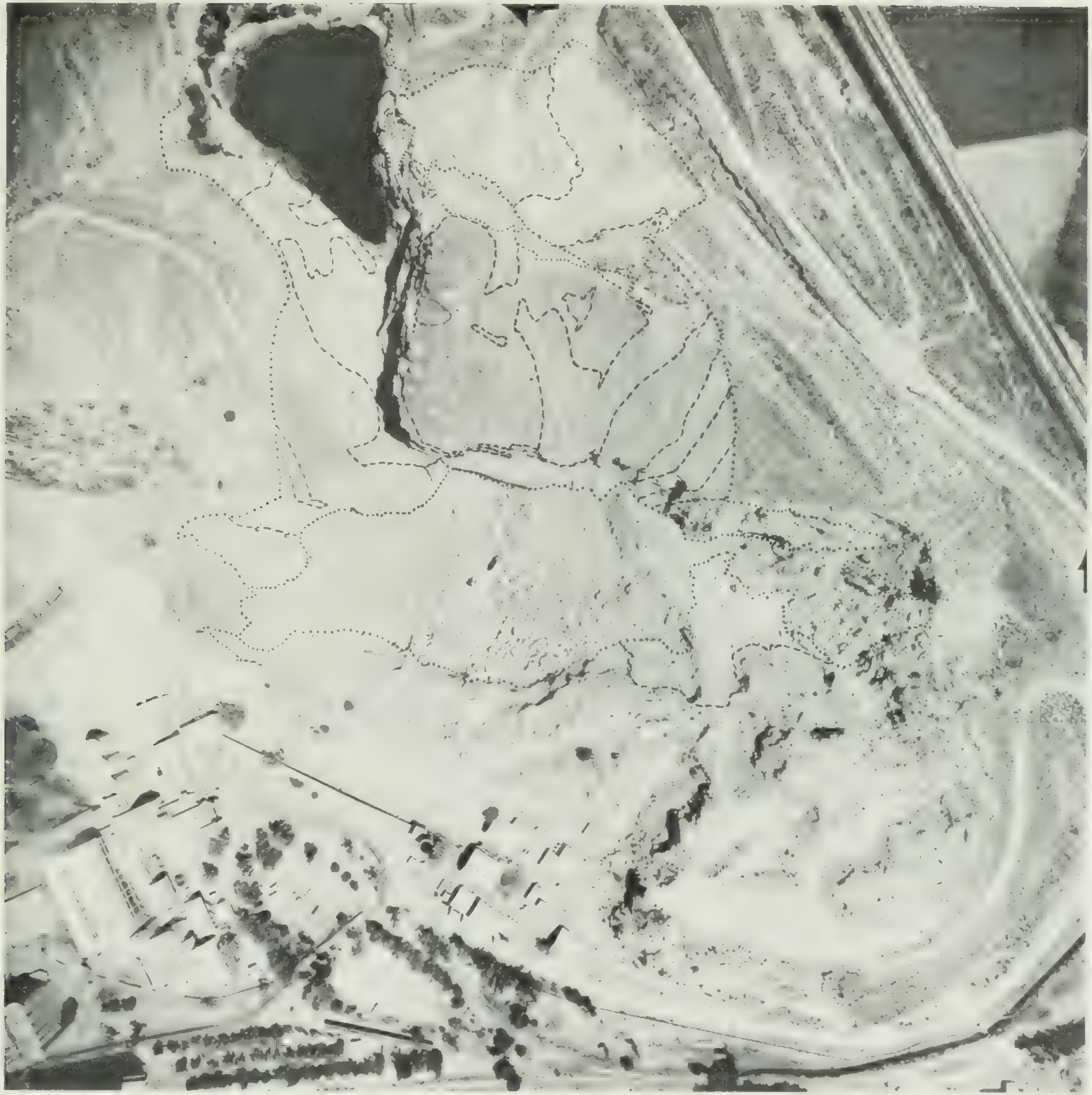

FIGURE 26. Air photograph of the Crestmore Hills and the plant and quarries of the Riverside Portland Cement Company. Contacts between major rock units are shown by means of dashed and dotted lines (see fig. 27). *MacPherson Aerial Surveys photo.*

50 feet west of the present east face of the caved area above the Crestmore mine, nor much beyond the south face of the Wet Weather quarry. The intrusion of this magma deformed the lower parts of the Sky Blue limestone into an eastward plunging anticline, the axis of which lies somewhat south of the ridge between the Commercial and Wet Weather quarries (figs. 26, 27).

In contrast to the minor metasomatic effects associated with the Bonsall tonalite, metasomatizing solutions from the porphyry magma, which were carrying mainly silica, alumina, and iron, produced a silicate contact aureole in the lower parts of the Sky Blue limestone that in places is as much as 50 feet thick. Approximately the inner two-thirds of this aureole consists principally of brown grossularite with lesser but variable amounts of diopside and wollastonite. Approximately the inner half of the remaining one-third of the aureole consists mainly of idocrase, whereas the outer half is characterized by monticellite. Important and highly variable amounts of other minerals associated with the monticellite include chondrodite, custerite, ellestadite, forsterite, melilite, merwinite, spinel, spurrite, tilleyite, and xanthophyllite. Retrograde hydrothermal alteration of all the mineral assemblages of the contact aureole resulted in formation of many hydrous minerals, among which are afwillite, chlorite, crestmoreite, hillebrandite, hydromagnesite, jurupaite (discredited?), nontronite, okenite(?), opal, riversideite (discredited?), and thaumasite.

Subsequent to its formation, the silicate contact aureole was intruded by pegmatites that originated in the crystallizing porphyry magma. Some of the dikes are zoned, with quartz cores that contain both wollastonite and calcite. Other pegmatitic bodies consist predominantly of quartz and/or calcite, and commonly contain a variety of minerals in addition to the major constituents. These minerals include allanite, apophyllite, axinite, centrallasite, clinozoisite, danburite, datolite, epidote, laumontite, opal, phillipsite, prehnite, scapolite, stilbite, and zoisite.

271.4 Bloomington. Turn left (west) onto U. S. Highway 70-99, and cross the broad alluvial plain of the San Bernardino Valley.

278.2 The Kaiser blast furnaces and steel plant are to the right (north). The principal raw material for this operation is magnetite-hematite ore from contact metamorphic deposits in the Eagle Mountains, in the eastern part of Riverside County. Continue westward into Ontario via A Street.[*]

288.2 Ontario. Cross Euclid Avenue.

292.1 Pomona. Cross Garey Avenue and continue westward on Holt Avenue.

294.2 Bear right onto U. S. Highway 60, and continue westward into Los Angeles by retracing the route outlined in the early part of this log.

295.2 Junction with freeway (U. S. Highway 70-99).

307.2 Bridge over San Gabriel River.

322.1 Los Angeles Civic Center, and end of the route.

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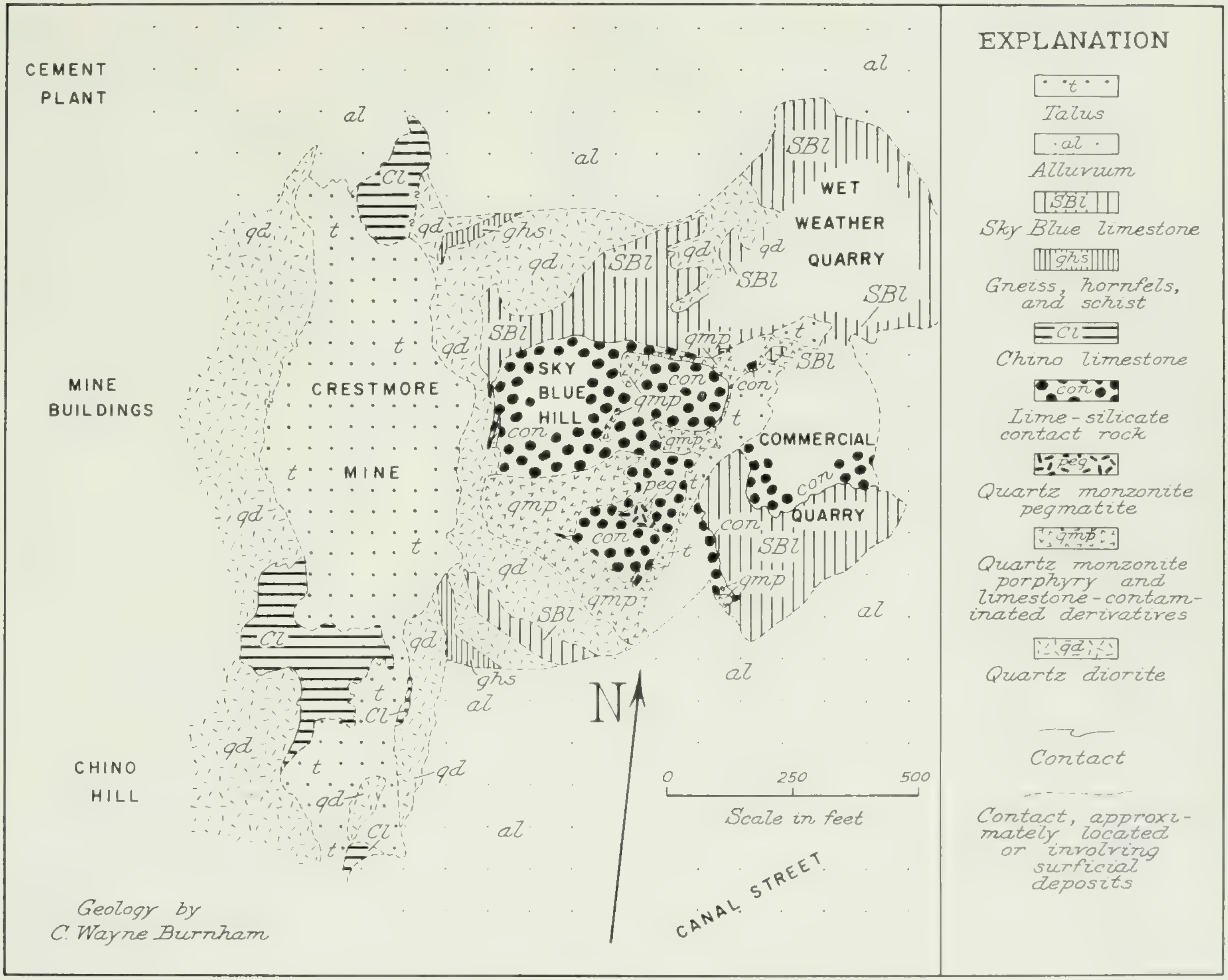
[*] The freeway to Los Angeles (new Highway 70-99, under construction at the time this road log was prepared) can be taken as an alternate route, but an adjustment in mileage figures should be made.


CEMENT PLANT
MINE BUILDINGS
CRESTMORE MINE
SKY BLUE HILL
WET WEATHER QUARRY
COMMERCIAL QUARRY
CHINO HILL
CANAL STREET
N
al
t
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Cl
ghs
SBl
qmp
con
peg
0 250 500
Scale in feet
Geology by C. Wayne Burnham
EXPLANATION
Talus
Alluvium
Sky Blue limestone
Gneiss, hornfels, and schist
Chino limestone
Lime-silicate contact rock
Quartz monzonite pegmatite
Quartz monzonite porphyry and limestone-contaminated derivatives
Quartz diorite
Contact
Contact, approximately located or involving surficial deposits

Figure 27. Geologic map of the Crestmore Hills, about 3 miles north of Riverside.

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